SECOND EDITION

PEDIATRIC & NEONATAL MECHANICAL VENTILATION

Praveen Khilnani

Foreword
RN Srivastava

JAYPEE

Pediatric and Neonatal Mechanical Ventilation

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Second Edition

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Dedicated to
my mother
Late Shrimati Laxmi Devi Khilnani
who left for heavenly abode on 13th May, 2001.
She always knew I could do it whenever I thought I couldn't.
She was the one who taught me to be always optimistic and hardworking.
God will take care of the rest.

Late Smt Laxmi Devi Khilnani
(19th Jan, 1930 – 13th May, 2001)

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Foreword

The author of this book, *Pediatric and Neonatal Mechanical Ventilation*, is an experienced pediatric intensivist with over 30 years of experience and expertise in the field of anesthesia, pediatrics and critical care. He has been involved in training and teaching at various conferences and mechanical ventilation workshops in India as well as at an international level. The text presented is intended to be a practical resource, helpful to beginners and advanced pediatricians who are using mechanical ventilation for newborns and older children.

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Preface to the Second Edition

After the first edition came out in 2006, *Pediatric and Neonatal Mechanical Ventilation* became instantly popular with pediatric residents in the Pediatric Intensive Care Unit (PICU) due to its small size and simple and practice-oriented approach.

Recently, more advances have come up in the field of mechanical ventilation including newer modes such as airway pressure release ventilation, neurally adjusted ventilatory assist (NAVA) and high frequency oscillatory ventilation (HFOV).

Newer ventilators with sophisticated microchip technology are able to offer better ventilation with precision with graphics and monitoring of dynamic parameters on a real-time basis as well as sophisticated alarm systems to check pressures (over distention) and volumes delivered to the patient via the breathing circuit (leaks if any). Newer advances such as FiO_2 weaning by feedback loop with real-time sensing of SpO_2 in the patient by the microchip built in the ventilator are soon going to be a reality.

In the second edition, newer chapters on specific scenarios of Ventilation in Asthma, ARDS, Extracorporeal Membrane Oxygenation (ECMO), Patient ventilator synchrony have been added. Flow charts have also been included in most of the chapters for ready reference. Some newer ventilators and their information have also been added in chapter on commonly available ventilators.

I sincerely hope that this book will continue to be of practical use to the residents and fellows in the pediatric and neonatal intensive care unit.

Praveen Khilnani

Preface to the First Edition

As the field of pediatric critical care is growing, the need for a simple and focused text of this kind has been felt for past several years in this part of the world for pediatric mechanical ventilation. Effort has been made to present the method and issues related to mechanical ventilation of neonate, infant and the older child. Basic and some advanced modes of mechanical ventilation have been described for advanced readers, topics like high frequency ventilation, ventilator graphics and inhaled nitric oxide have also been included. Finally, some commonly available ventilators and their features and utility in this part of the world have been discussed. I hope this book will be helpful to pediatricians, residents and neonatal pediatric intensivists who are beginning to work independently in an intensive care setting, or have already been involved in care of critically ill neonates and children.

Praveen Khilnani

Acknowledgments

Besides a description of available evidence and using my personal experience of mechanical ventilation of neonates and children for past 20 years, I have taken the liberty of using the knowledge and experience of my teachers Prof I David Todres (Professor of Anesthesia and Pediatrics, Harvard University, Boston, MA), Prof William Keenan (Director of Neonatology, Glennon Children Hospital, St Louis University, St Louis, MO), Prof Uday Devaskar (Director of Neonatology, UCLA, CA), and authorities such as Dr Alan Fields (PICU, Children's National Medical Center, Washington DC), and Robert Kacemarek (Director, Respiratory Care at Massachusetts General Hospital, Boston, MA).

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Finally, the acknowledgment is due to my family without whose whole-hearted support this task could not have been accomplished.

Contents

1 Chapter

Structure and Function of a Conventional Ventilator

Praveen Khilnani, S Ramesh

This chapter is intended to get the reader familiar with basic aspects of the ventilator as a machine and its functioning. We feel this has important bearing in the management issues of a critically-ill child requiring mechanical ventilation.

VENTILATOR

A ventilator is an automatic mechanical device designed to move gas into and out of the lungs. The act of moving the air into and out of the lungs is called breathing, or more formally, ventilation.

Simply, compressed air and oxygen from the wall is introduced into a ventilator with a blender, which can deliver a set FiO_2. This air oxygen mixture is then humidified and warmed in a humidifier and delivered to the infant by the ventilator via the breathing circuit.

The peak inspiratory pressure (PIP) or tidal volume (Vt), positive end expiratory pressure (PEEP), inspiratory time and respiratory rate are set on the ventilator.

The closing of the exhalation valve initiates a positive pressure mechanical breath. At the end of the preset inspiratory time, the exhalation valve is opened, permitting the infant to exhale. If this end is partly occluded during expiration, a PEEP is generated in the circuit proximal to the occlusion (or CPAP if the infant is breathing spontaneously). Expiration is passive and gas continues to flow delivering the set PEEP.

Parts of a Ventilator

1. *Compressor:* This is required to provide a source of compressed air. An in-built wall source of compressed air, if available, can be used instead. It draws air from the atmosphere and delivers it under pressure (50 PSI) so that the positive pressure breaths can be generated.

The compressor has a filter which should be washed with tap water daily or as directed. If this is not done, it greatly increases the load on the compressor. The indicator on the compressor should always be in the green zone. It should not be placed too close to the wall as it may get overheated. There should be enough space to permit air circulation around it.

2. *Control panel:* The controls that are found on most pressure-controlled ventilators include the following:
   - FiO_2
   - Peak Inspiratory Pressure: PIP (in pressure controlled ventilators).
   - Tidal volume / Minute volume (in volume controlled ventilators).
   - Positive End Expiratory Pressure (PEEP).
   - Respiratory Rate (RR).
   - Inspiratory Time (Ti).
   - Flow rate.

   The other parameters displayed on the ventilator include mean airway pressure (MAP), I:E ratio (ratio of the inspiratory time to expiratory time). The expired tidal volume will be displayed in all volume controlled ventilators and some pressure controlled ventilators.

   Newer ventilator models have digital display controls. Some ventilators also display waveforms, which show the pulmonary function graphically.
3. *Humidifier:* Since the endotracheal tube bypasses the normal humidifying, filtering and warming system of the upper airway, the inspired gases must be warmed and humidified to prevent hypothermia, inspissation of secretions and necrosis of the airway mucosa.
   Types of humidifiers available:
   a. *Simple humidifier:* It heats the humidity in inspired gas to a set temperature, without a servo control. The disadvantage is excessive condensation in the tubings with reduction in the humidity along with cooling of the gases by the time they reach the patient.
   b. *Servo-controlled humidifier with heated wire in the tubings:* These prevent accumulation of condensate while ensuring adequate humidification. Optimal temperature of the gases should be 36-37°C and a relative humidity of 70 percent at 37°C. If the baby is nursed in the incubator, temperature monitoring must take place before the gas enters the heated field. At least some condensation must exist in the inspiratory limb which shows that humidification is adequate. The humidifier chamber must be changed daily. It should be adequately sterilized or disposable chambers may be used.
4. *Breathing circuit:* It is preferable to use disposable circuits for every patient. Special pediatric circuits are available in the market with water traps. If reusable circuits are used, they must be changed every 3 days. Reusable circuits are sterilized by gas sterilization or by immersion in 2 percent glutaraldehyde for 6-8 hours and then thoroughly rinsing with sterile water. Disposable circuits may be changed every week.

Terminology

Ventilatory controls that can be altered in mechanical ventilation include the following:
1. Inspired oxygen concentration (FiO_2).
2. Peak inspiratory pressure (PIP).

3. Flow rate.
4. Positive end-expiratory pressure (PEEP).
5. Respiratory rate (RR),or Frequency (f).
6. Inspiratory / Expiratory Ratio (I:E Ratio).
7. Tidal volume (in volume controlled ventilators).
8. Pressure support.

Inspired Oxygen Concentration (FiO_2)

An improvement in oxygenation may be accomplished either by increasing the inspired oxygen concentration (FiO_2) or by different ventilator settings.

1. Increasing peak inspiratory pressure (PIP)
2. Increasing inspiratory / expiratory ratio
3. Applying a positive pressure before the end of expiration (PEEP).

FiO_2 is adjusted to maintain an adequate PaO_2. High concentrations of oxygen can produce lung injury and should be avoided. The exact threshold of inspired oxygen that increases the risk of lung injury is not clear. A FiO_2 of 0.5 is generally considered safe. In patients with parenchymal lung disease with significant intrapulmonary shunting, the major determinant of oxygenation is lung volume which is a function of the mean airway pressure. With a shunt fraction of > 20 percent oxygenation may not be substantially improved by higher concentrations of oxygen.

The administration of oxygen and its toxicity is a clinical problem in the treatment of neonates, especially low birth weight infants.

The developing retina of the eye is highly sensitive to any disturbance in its oxygen supply. Oxygen is certainly a critical factor (hyperoxia, hypoxia), but a number of other factors (immaturity, blood transfusions, PDA, vitamin E deficiency, infections) may interact to produce various degrees of Retinopathy of Prematurity (ROP).

Another complication of oxygen toxicity induced by artificial ventilation in the neonatal period is a chronic pulmonary disease, Bronchopulmonary Dysplasia (BPD), mostly seen in premature infants ventilated over long periods with a high inspiratory peak pressure and high oxygen concentration.

High oxygen concentration may play a role in the pathogenesis of BPD, but recent studies have shown, that the severity of the disease is correlated to the Peak inspiratory pressure (PIP) during artificial ventilation rather than to the doses of supplementary oxygen.

Peak Inspiratory Pressure (PIP)

Peak Inspiratory Pressure is the major factor in determining tidal volume in infants treated with time cycled or pressure cycled ventilators. Most ventilators indicate inspiratory pressure on the front and it can be selected directly.

The starting level of PIP must be considered carefully. Critical factors that must be evaluated are the infant's weight, gestational age (the degree of maturity), the type and severity of the disease and lung mechanics—such as lung compliance and airway resistance.

The lowest PIP necessary to ventilate the patient adequately is optimal. In most cases, associated with increased tidal volume, increased CO_2 elimination and decreased $PaCO_2$.

Mean airway pressure will rise and thus improve oxygenation.

If PIP is minimized, there is a decreased incidence of barotrauma with resultant air leak (pneumothorax and pneumomediastinum) and BPD.

Hacker *et al* demonstrated that more rapid ventilator rates and lower PIP are associated with a decreased incidence of air leaks—a mode of ventilation which may be recommended in infants with congenital diaphragmatic hernia.

High PIP may also impede venous return and lower cardiac output.

Flow Rate

The flow rate is important determinant during the infant's mechanical ventilation of attaining desired levels of peak inspiratory pressure, wave form, I:E ratio and in some cases, respiratory rate.

In general, a minimum flow at least two times the minute volume ventilation is usually required. Most pressure ventilators operate at flows of 6-10 liters per minute.

If low flow rates are used, there will be a slower inspiratory time (Ti) resulting in a pressure curve of sine wave form and lowering the risk of barotrauma.

Too low flow relative to minute volume, may result in hypercapnia and accumulation of carbon dioxide in the system.

High inspiratory flow rates are needed if square wave forms are desired and also when the inspiratory time is shortened in order to maintain an adequate tidal volume. Carbon dioxide retention in the ventilator tubing will be prevented at high flow rates.

A serious side effect of high flow rate is an increased risk of alveolar rupture, because maldistribution of ventilation results in a rapid pressure increase in the non-obstructed or non-atelectatic alveoli.

Positive End Expiratory Pressure (PEEP)

Positive pressure applied at the end of expiration to prevent a fall in pressure to zero is called Positive End Expiratory Pressure (PEEP).

PEEP stabilizes alveoli, recruits lung volume and improves the lung compliance. The level of PEEP depends on the clinical circumstances. Application of PEEP results in a higher mean airway pressure, and mean lung volumes.

The goals of PEEP are:

1. Increasing FRC (Functional Residual Capacity) above closing volume to prevent alveolar collapse
2. Maintaining stability of alveolar segments
3. Improvement in oxygenation, and
4. Reduction in work of breathing.

The optimum PEEP is the level at which there is an acceptable balance between the desired goals and undesired adverse effects. The desired goals are: (1) reduction in inspired oxygen concentration—nontoxic levels (usually less than 50%); (2) maintenance of PaO_2 or SaO_2 of > 60 mm Hg or > 90 percent respectively, (3) improving lung compliance; and (4) maximizing oxygen delivery.

Arbitrary limits cannot be placed to determine the level of PEEP or mean airway pressure that will be required to maintain adequate gas exchange. When the level of PEEP is high, peak inspiratory pressure may be limited to prevent it from reaching dangerous levels that contribute to air leaks and barotrauma. In children with tracheomalacia or bronchomalacia, PEEP decreases the airway resistance by distending the airways and preventing dynamic compression during expiration.

The compliance may be improved. Improved ventilation may result (improvement in ventilation / perfusion ratio) by preventing alveolar collapse.

Low levels of PEEP (2-3 cm H_2O) are often used during weaning from the ventilator in conjunction with low IMV rates only for a short amount of time.

Medium levels of PEEP (4-7 cm H_2O) are commonly used in moderately ill patients.

High levels of PEEP (8-15 cm H_2O) benefit oxygenation in ARDS (Acute Respiratory Distress Syndrome); tidal volume, and PaO_2 increases. Higher PEEP level can also reduce blood pressure and cardiac output explained by a reduced preload. Very high levels of PEEP results in over-distention and alveolar rupture leading to increased incidence of pneumothorax and pneumomediastinum.

Respiratory Rate (RR) or Frequency (f)

Respiratory rate, together with tidal volume, determines the minute ventilation. Depending on the infant's gestational age and the underlying disease, the resulting pulmonary mechanics (resistance, compliance) require the use of slow or rapid ventilatory rates.

Moderately high ventilator rates (60-80 breaths per minute) employ a lower tidal volume and therefore, lower inspiratory pressures (PIP) are used to prevent barotrauma.

High rates may also be required to hyperventilate infants with pulmonary hypertension and right-to-left shunting to achieve an increased pH and reduced $PaCO_2$, thereby reducing pulmonary arterial resistance and shunting associated with increased $PaCO_2$. Respiratory rate is the primary determinant of minute ventilation and hence, CO_2 removal from lungs.

Tidal volume × RR, increasing the RR lowers the $PaCO_2$ level. A respiratory rate of 40-60 is usually sufficient in most conditions. High rates are necessary in Meconium Aspiration Syndrome (MAS) where CO_2 retention is a major problem. It must be recognized that increasing the RR while keeping the IT the same, shortens expiration and may lead to inadequate emptying of lungs and inadvertent PEEP.

One of the major disadvantages in using the high ventilator rates is an insufficient emptying time during the expiratory phase, resulting in air trapping, increased FRC, and thus decreased lung compliance.

A slow ventilation rate combined with a long inspiratory time, both in animals and infants with RDS resulted in fewer bronchiolar histological lesions, better lung compliance and in infants, a reduction in the incidence of BPD.

Ratio of Inspiratory to Expiratory Time (I:E ratio)

One of the most important ventilator control is the ratio of inspiratory to expiratory time (I:E ratio). This ventilator control has to be adjusted depending on the pathophysiology and the course of the respiratory disease, always with respect to pulmonary mechanics, such as compliance, resistance and time constant.

In infants with, Respiratory Distress syndrome (RDS) with decreased compliance but normal resistance, resulting in shortened time constants inspiratory times I:E with ratios 1:1 are usually used.

Reversed I:E ratios, as high as 4:1 have been shown to result in improvement in oxygenation and in a retrospective study decreased the incidence of BPD. Other investigators also advocated the use of prolonged inspiratory time, since infants in the '2:1' group required less inspired oxygen and a lower expiratory pressure to achieve satisfactory oxygenation. Extreme reversed I:E ratio with a short expiratory time will lead to air trapping and alveolar distention. In addition, prolonged inspiratory time may adversely affect venous return to the heart and decreased pulmonary and systemic blood flow. The concept becomes especially important when higher respiratory rates are used.

If inspiratory time is shorter than three to five time constants, inspiration will not be complete and tidal volume will be lower than expected. If expiratory time is too short, expiration will not be complete which will lead to air trapping.

An IT of 0.3-0.5 sec is sufficient for most disorders. In low compliance condition like RDS use closer to 0.5 sec. In disorders with increased airway resistance like MAS use shorter IT. Once set, IT is usually not changed unless there is persistent hypoxemia unresponsive to changes in PIP and FiO_2.

Increasing the IT shortens the expiratory time increasing the I:E ratio. Normal ratio is 1:3. Avoid 1:1 ratio to prevent air trapping.

While ventilating a case of lower airways obstruction (asthma, bronchiolitis) use short IT and slow rate with a longer expiratory time as there is gas trapping and increased risk of air leaks.

Tidal Volume (Vt)

In most volume cycled ventilators, tidal volume of 6 to 8 ml / kg can be set, or a particular flow rate and minute ventilation can be set to get a particular tidal volume. Siemens Servo 300 ventilator measures expired tidal volume and gives a display. If set tidal volume is significantly (the difference

between set inspired and expired tidal volume is more than 15%) higher than the expired tidal volume, then circuit leak or an endotracheal leak should be looked for and corrected.

Pressure-support

Pressure-support ventilation is a form of assisted ventilation where the ventilator assists a patient's spontaneous effort with a mechanical breath with a preset pressure limit. The patient's spontaneous breath creates a negative pressure, which triggers the ventilator to deliver a breath. The breath delivered is pressure-limited; very high inspiratory flow results in a sharp rise in inspiratory pressure to the preset pressure limit. The inspiratory pressure is held constant by servo-control of the delivered flow and is terminated when a minimal flow is reached (usually < 25% of peak flow), just before spontaneous exhalation begins. Pressure-support ventilation depends entirely on the patient's effort, if the patient becomes apneic, the ventilator will not provide any mechanical breath. Pressure-support ventilation allows better synchrony between the patient and the ventilator than IMV, volume-assisted ventilation, or pressure control ventilation. Pressure-support allows ventilatory muscle loads to be returned gradually during the weaning process like IMV techniques. Since each breath is assisted, it alters the pressure volume relationship of the respiratory muscles in such a way so as to improve its efficiency. With ventilatory muscle fatigue, muscles can be slowly retrained and titrated more efficiently than IMV and thus, promote the weaning process. The emphasis with weaning with pressure support ventilation is endurance training of the respiratory muscles, especially, the diaphragm. The parameters that can be manipulated to titrate the muscle loading are the magnitude of the trigger threshold and the preset pressure limit. PEEP is provided to maintain FRC and prevent alveolar collapse. The amount of pressure-support to be provided depends on the clinical circumstance. A pressure-limit that delivers a VT of 10 to 12 ml/kg has been termed PSV max because at this level respiratory work can be reduced to zero. It is not necessary to provide PSV max at the beginning. The level of pressure support selected should allow for spontaneous respiration without undue exertion and still results in normal minute ventilation. No strict criteria can be established; it has to be applied and titrated on an individual basis. Weaning of pressure-support ventilation is accomplished by reducing the pressure-limit decrementally. Similar to weaning guidelines previously mentioned with each wean, the effect of weaning on muscle loading has to be evaluated clinically. Increase in respiratory rate is an early indication of increasing muscle load. Retraction and use of accessory muscles would indicate a more severe muscle load. If respiratory rate increases during the weaning process, the level of pressure-support should be increased until there is reduction in the respiratory rate. While this method of weaning is attractive theoretically, its benefit in the weaning process is yet to be established in infants and children. A relative contraindication to the use of pressure-support ventilation is a high baseline spontaneous respiratory rate. There is a finite lag time involved from the initiation of a breath to the

sensing of this effort and from the sensing to the delivery of a mechanical breath. In infants breathing at a relatively fast rate (40 to 50 breaths/minute), this lag time may be too long and result in asynchrony between the patient and the ventilator. Pressure-support has been mainly used to wean adult patients off mechanical ventilation. Its use in pediatrics is gaining popularity. When used at our institution, we tend to keep a base line low SIMV rate (5 to 6 per min) along with pressure support before extubation.

2 Chapter

Mechanical Ventilation: Basic Physiology

Praveen Khilnani

It is essential to understand basic respiratory physiology to understand and manage the disease process involving the lungs, upper or lower airways, alveoli or all of the above. In addition, understanding of central regulation of respiration as well as neuromuscular factors affecting the respiratory mechanics is as important.

BASIC RESPIRATORY PHYSIOLOGY

The purpose of the lung is to exchange oxygen and carbon dioxide across the alveolar capillary membrane.

Growth of the distal airway lags behind that of the proximal airway during the first five years of life. The relatively narrow distal airway until the age of five years, presumably accounts for the high peripheral airway resistance in this age group. The relative weakness of cartilaginous support in infants compared to adults may lead to dynamic compression of the trachea in situations associated with high expiratory flow rates and increased airway resistance such as bronchiolitis, asthma or even crying. After birth, there is a dramatic increase in the number of alveoli. At birth, 20 million; by age 8, the number of alveoli increase to 300 million. After the age of 8, it is not clear whether alveolar multiplication continues or it is just the alveolar enlargement. At birth, alveolar surface area is 2.8 square meters. By 8 years of age, the alveolar surface area has increased to 32 square meters. Adult alveolar surface area is 75 square meters. In infants, diffusing capacity is only 1/3 to 1/2 of that of adults even when normalized to body surface area.

Collateral ventilation in adults takes place by interalveolar pores of Kohn, bronchioalveolar channels which are Lambert's channels and interbronchiolar channels.

Collateral ventilation starts happening sometimes after the first year of life. Lambert's channels start appearing around six years of age. Interbronchiolar channels have been found in diseased lungs only.

Airway Resistance

In children, peripheral airway resistance is four times higher than that of adults or older children. In adults, the majority of airway resistance comes from upper airway, particularly the nose. This explains why lower airway

obstructive disease is much more common in infants secondary to inflammation, which makes them symptomatic.

Distribution of Inspired Gas

Dead space ventilation: Dead space could be anatomical, physiological dead space or alveolar dead space.

Anatomical dead space cannot participate in gas exchange.

Physiological dead space is equal to anatomic dead space plus the alveolar dead space.

Normal dead space to tidal volume ratio is 3 (VD / VT).

Physiological dead space can be calculated by:

$$PaCO_2 - PeCO_2 \times \frac{\text{Minute ventilation}}{PaCO_2}$$

(e = expired)

(a = arterial)

Three zones in the lung that are physiologically different, have been defined by West (Fig. 2.1).

In West zone 1, the alveolar pressure is higher than the arterial pressure, is higher than venous pressure.

In West zone 2, the arterial pressure is higher than the alveolar pressure, is higher than the venous pressure.

*In West zone 3***,** the arterial pressure is higher than the venous pressure, is higher than the alveolar pressure.

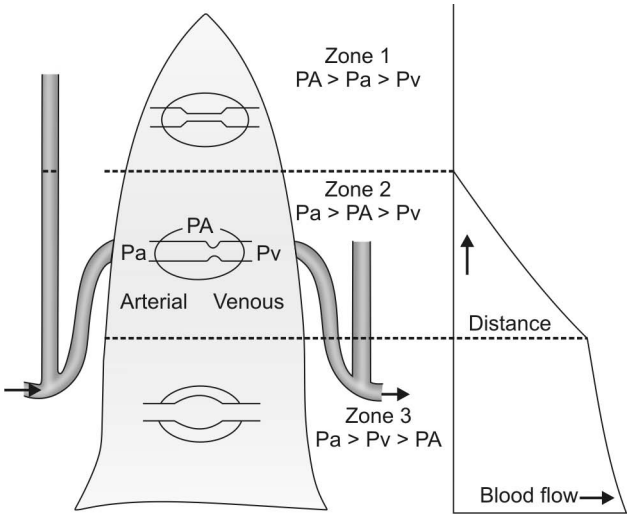

Fig. 2.1: Zone of perfusion in the lung

(Redrawn from West JB, Dollery CT, Naimark A: J Appl Physio 1964;19:713)

Dependent alveoli at the base of the lungs expand more for a given change in pressure. This is fortunate because the greater portion of pulmonary blood flow also goes to dependent lung regions.

However, if the alveoli in the dependent regions get too small, they could collapse. Closing capacity is defined as the sum of the closing volume, and the residual volume.

PEEP (positive end expiratory pressure) is designed to raise the FRC(functional residual capacity) above the closing capacity.

Children younger than six years of age have a closing capacity greater than FRC in supine position. This is due to reduced elastic recoil of the lungs.

Transpulmonary Pressure

During breathing, the transpulmonary pressure must be generated in order to overcome the opposing forces of the elastic recoil as well as the force due to frictional resistance to gas flow. The inertial force of respiratory system is negligible.

Compliance

Compliance is change in volume per unit change in pressure. Lung compliance depends on the elasticity of lung tissue and on initial lung volume before inflation**.** Stiff lung means low compliance, expansile lung means high compliance.

Greater pressure gradient must be generated in order to inflate a lung from a very low lung volume.

Therefore, specific compliance is the lung compliance per unit FRC.

Specific compliance in newborn and adult is the same. Reciprocal of total compliance equals to the reciprocal of chest wall compliance plus the reciprocal of lung compliance.

- Elastance is reciprocal of compliance.
- Pressure is equal to flow times resistance.

In laminar flow, the resistance varies inversely with the 4th power of the radius. In turbulent flow, the resistance varies with the 5th power of the radius.

In turbulent flow, density of the gas is more important than the viscosity.

Helium / oxygen mixtures having very low density have been used in upper airway obstruction. Helium / oxygen mixture has a lower density than air oxygen.

Conductance is the Reciprocal of Resistance

In BPD (bronchopulmonary dysplasia) and Alfa 1 antitrypsin deficiency, because of poor cartilageous support, airway collapses when active expiration occurs.

Time constant (resistance compliance) is the time needed for the lung unit to reach 63 percent of its final volume. Slow alveoli take longer to fill and so they have a longer time constant. That could be due to either their resistance being too high or their compliance being high.

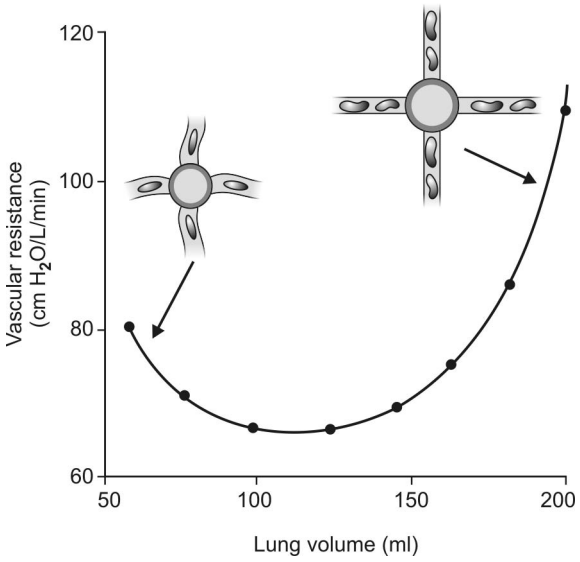

Fig. 2.2: Relationship between lung volume and vascular resistance

(Redrawn from West JB: Blood flow. In: Respiratory physiology—the essentials, Baltimore, 1979, Williams & Wilkins)

Given a particular time constant, resistance would then be inversely proportional to the compliance.

Laplace equation is: pressure equals two times the surface tension divided by the radius R. It predicts that small alveoli empties into larger ones resulting into the ultimate collapse of small alveoli, and overdistention of larger alveoli.

Surfactant lines the walls of the alveoli and prevents collapse. Therefore, one needs smaller distending airway pressure to keep alveoli open.

Pulmonary blood flow is best at FRC, approximately at lung volume of 120 ml (Fig. 2.2). At lower lung volume, the teethering action of the tortuous vessels causes vascular resistance to go up, and at higher volumes physical compression of the vasculature occurs, thereby increasing the vascular resistance.

At both, too low and too high volumes, the pulmonary blood flow is poor. Pulmonary blood volume is increased in the supine position. Average values of pulmonary artery pressure are 22 / 8 mm Hg with a mean of 15 mm Hg.

The difference between the pulmonary arterial pressure and the left atrial pressure is the driving pressure for the pulmonary blood in the vascular tree.

Ventilation (V) Perfusion (Q) Ratio

During positive pressure ventilation, the driving pressure is pulmonary arterial pressure minus the pulmonary alveolar pressure. Apical regions of the lung are underperfused, therefore VQ (ventilation is three times

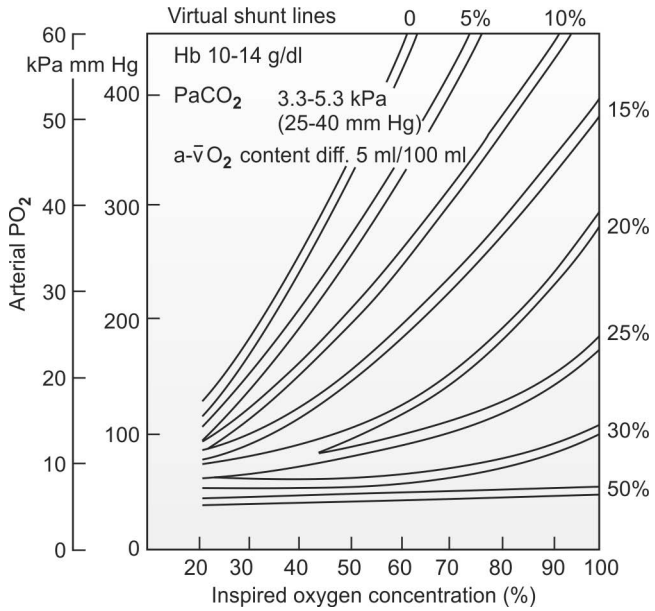

Fig. 2.3: ISO shunt diagram. The ISO shunt bands are widened to include the indicated range of $PaCO_2$ and hemoglobin (HB)

(From Benatar SR, Hewlett AM, Nunn JF: Br J Anaesth 1973; 45:711)

more than perfusion) ratio is about 3. Basal regions are somewhat underventilated, so VQ ratio is 0.6.

Shunt

Shunt refers to the venous blood that has travelled from right side of the circulation to the left side without ever coming in contact with the ventilated lung. Therefore, VQ ratio is 0.

Examples of shunt include: normal bronchial and thebesian circulations, or blood flow through the collapsed lung, and cyanotic congenial heart disease with blood flow from the right side of the heart to the left side. Figure 2.3 shows ISO shunt diagram. Increasing inspired oxygen concentration will usually compensate for small areas of shunting in the lung. Note if the shunt is 50 percent (say if one lung is collapsed, getting only perfused but not ventilated, and the other lung is normally ventilated and perfused, even 100 percent oxygen will not achieve > 80 mm Hg arterial PaO_2.

Dead space: means there is ventilation, but no perfusion to that space. VQ ratio is equal to infinity.

At 25 percent of shunt, 100 percent oxygen can get the PaO_2 as high as 150, but at 50 percent shunt, 100 percent oxygen will not raise the PaO_2 above 80-90.

Arterial PCO_2 equals alveolar ventilation divided by CO_2 production.

A large admixture of venous blood to the pulmonary capillary would produce only a small increase in the arterial PCO_2. Normal term newborn has a lower PO_2 than the adult. The reason for that is increased venous admixture which probably arises mainly from a combination of right to left shunting through persistent fetal vascular channels, and at atelectatic areas of the lungs.

Diffusing Capacity

It is equal to flow divided by the driving pressure. Diffusing capacity increases with age, height and body surface area reflecting the increase in diffusing capacity with increasing total surface area available for diffusion.

The rate of flow of fluid in the lungs is equal to the difference of capillary and interstitial hydrostatic pressure minus the difference in plasma and interstitial oncotic pressures. Hydrostatic pressure gradient drives fluid into the interstitium and oncotic pressure gradient tries to keep the fluid intravascular.

Hydrostatic pressure can be increased by increasing blood volume, increasing left atrial pressure, increasing pulmonary blood flow from a large left to right shunt. Pulmonary edema usually does not develop until the capillary hydrostatic pressure will go more than 25 mm of mercury beyond the normal oncotic pressure. Hydrostatic pressure in the interstitial space is believed to be somewhat negative under normal circumstances. Hypoproteinemia, even though it will reduce oncotic pressure, usually does not cause pulmonary edema as long as alveolar capillary membrane is intact.

Lymphatic channels in the interstitial space clear the excess interstitial fluid and protein. This is an important safety mechanism, when overwhelmed in congestive heart failure or with lymphatic obstruction due to injury to the lymphatic channels secondary to Fontan operation, it may result in pulmonary edema / effusion.

Oxygen Carriage

Hemoglobin is the main carrier (HbO_2 saturation) of O_2 / 1.34 ml / gm. PaO_2 is O_2 tension exerted by oxygen in physical solution in plasma (0.003 ml / mm Hg PaO_2), responsible for gradient for oxygen to bind with hemoglobin.

Term newborns have 70 percent hemoglobin F and 30 percent hemoglobin A. By the end of the first six months of life, hemoglobin A has replaced hemoglobin F and only trace levels of hemoglobin F are detectable. The P 50 for Hemoglobin F is 19 compared to P 50 of 27 (the PaO_2 level at which the hemoglobin is 50 percent saturated) for hemoglobin A. Acidosis, increased 2, 3 diphosphoglycerate (2, 3 DPG) (stored blood has depletion of 2, 3 DPG) shift the oxyhemoglobin dissociation curve to right, meaning easier dissociation of oxygen from hemoglobin (Fig. 2.4). Fetal hemoglobin binds tightly to oxygen (curve shifted to left). Hemoglobin S differs from hemoglobin A by the substitution of valine for glutamic acid at position 6. Hemoglobin S has a lower P 50. Methemoglobin cannot bind oxygen.

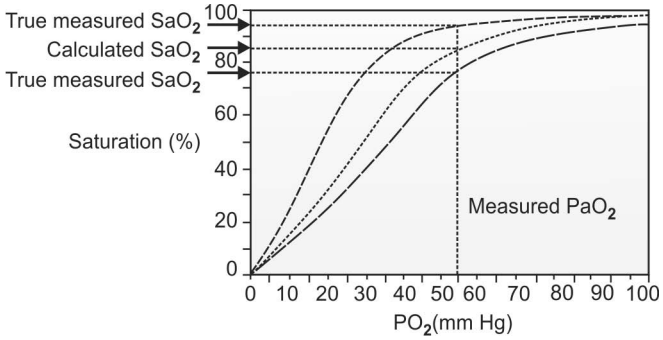

Fig. 2.4: Oxyhemoglobin-dissociation curves

If the percentage of methemoglobin is more than 30-40 percent, the patient becomes symptomatic. 1 mg / kg of 1 percent methylene blue can be given**.**

The affinity of CO (carbon monoxide) to the hemoglobin molecule is 210 times greater than the affinity of oxygen for hemoglobin. In modern blood gas analyzer, O_2 saturation is often calculated using a measured oxygen tension and assuming a normaly placed oxyhemoglobin-dissociation curve. If the curve is shifted to the right or left, the calculated value of saturation will be different than the true measured value. The major source of error is that blood gas analyzers assume a normal concentration of 2.3-DPG and thus, a normally placed curve.

Carbon monoxide increases the binding of oxygen for hemoglobin and does shift the position of oxyhemoglobin dissociation curve to the left. It also decreases peripheral utilization of oxygen.

Critical tissue level of mitochondrial PO_2 is thought to be around 1 mm of mercury.

Critical jugular venous oxygen saturation is 24 percent, because less than 24 percent results in unconsciousness.

Oxygen extraction ratio is the ratio of oxygen consumption to oxygen delivery.

It can be calculated by arterial venous oxygen content difference divided by arterial oxygen content. Normal extraction ratio is 25.

Control of Respiration

Three respiratory control centers exist:

- Pneumotaxic center, Apneustic center and the Medullary center.
- Medullary center is located in the medulla and is most important for respiration.
- Pneumotaxic center fine tunes inspiration to expiration.
- Both Pneumotaxic and Apneustic centers which are located in the pons are not necessary for normal control of respirations.

Chest Mechanics

Diaphragmatic fatigue in premature infants may be explained because of longer contractions and longer relaxation time and less sarcoplasmic

reticulum in the muscle fibers, and therefore, a need of more substrate for contraction and relaxation.

Chest wall in newborns is more compliant, therefore, gets sucked in with each inspiratory movement if there is respiratory distress, and therefore work of breathing is more.

Infants breathe more close to their closing capacity.

Hypoxia depresses CO_2 response in newborns. Hypoxia alone also depresses ventilation, more so in premature neonates. Phrenic nerve paralysis causes more trouble in newborns compared to adults because the intercostal stabilizing mechanisms are not that good. Thus, unilateral phrenic nerve paralysis in the infant develops into a massive flail chest because the paralyzed diaphragm and ribs are all sucked into the chest with active inspiration. C-spine (cervical spine) injury at the level below C5 may result in respiratory compromise because even though function of the diaphragm remains intact, paralysis of intercostal muscles causes severe chest wall retraction during active inspiration. Respiratory muscles perform approximately half their work on inspiration. Respiratory muscles have to overcome tissue elastic resistance. The second major source of resistance is friction generated by the gas flowing through the airways. A combination of these two determines how much total work inspiratory muscles have to do. Hypoventilation leads to hypercarbia and hypoxia with hypoventilation PaO_2 falls first slowly, and then rapidly as the alveolar ventilation falls. Furthermore, with the raised inspired oxygen pressure or a lower oxygen consumption, even greater degrees of hypoventilation would be needed to produce alveolar hypoxia.

APPLIED RESPIRATORY PHYSIOLOGY FOR MECHANICAL VENTILATION

Mechanical ventilation in children and neonates is different from adults.

While basic principles of Physics and gas flow apply to all age groups, anatomical and physiological differences play a significant role in selecting the type of ventilator as well as the ventilatory modes and settings.

Upper airway in children is cephalad, funnel-shaped with narrowest area being subglottic (at the level of cricoid ring), as compared to adults where the upper airway is tubular with narrowest part at the vocal cords.

Airway resistance increases inversely by 4th power of radius, i.e. in an already small airway, even one mm of edema or secretions will increase the airway resistance and turbulent flow markedly necessitating treatment of airway edema, suctioning of secretion and measures to control secretions.

Low functional residual capacity (FRC :Volume of air in the lungs at the end of expiration) reduces the oxygen reserve, reduces the time that apnea can be allowed in a child.

Respirations are shallow and rapid due to predominant diaphragmatic breathing and inadequate chest expansion due to inadequate costovertebral bucket handle movement in children. Therefore, a child tends to get tachypneic rather than increasing the depth of respiration in response to hypoxemia.

Oxygen consumption/kg body weight is higher, therefore, tolerance to hypoxemia is lower.

Susceptibility to bradycardia in response to hypoxemia is also higher due to high vagal tone.

Pores of Kohn and channels of Lambert (brochoalveolar and interalveolar collaterals) are inadequately developed making regional atelectasis more frequent.

Closing volumes are lower and airway collapse due to inadequate strength of the cartilage in the airways is common making a child particularly susceptible to laryngomalacia, and tracheobronchomalacia as well as lower airways closure.

Therefore, children tend to require smaller tidal volumes, faster respiratory rates, adequate size uncuffed endotracheal tube, adequately suctioned clear airway for proper management of mechanical ventilation.

Gradient between mouth and pleural space is the driving pressure for the inspired gases and this gradient is needed to overcome resistance and to maintain alveolus open, by overcoming elastic recoil forces.

Therefore, a balance between elastic recoil of chest wall and the lung determines lung volume at any given time. Normal inspiration is actively initiated by negative intrathoracic pressure driving air into the lungs. Expiration is passive.

Ventilation

Ventilation washes out carbon dioxide from alveoli keeping arterial $PaCO_2$ between 35-45 mm of Hg. Increasing dead space increases the $PaCO_2$.

$$PaCO_2 = k \times \frac{\text{Metabolic production}}{\text{Alveolar minute ventilation}}$$

Alveolar MV = respiratory rate x effective tidal volume

Effective TV = TV – dead space

Dead space = Anatomic (nose, pharynx, trachea, bronchi) + Physiologic (alveoli that are ventilated but not perfused)

Adequate minute ventilation is essential to keep $PaCO_2$ within normal limits.

Oxygenation

Partial pressure of oxygen in alveolus (P_AO_2) is the driving pressure for gas exchange across the alveolar-capillary barrier determining oxygenation.

$P_AO_2 = (\{\text{Atmospheric pressure} - \text{water vapor}\} \times FiO_2) - PaCO_2 / RQ$

RQ= respiratory quotient

Adequate perfusion to alveoli that are well-ventilated improves oxygenation.

Hemoglobin is fully-saturated 1/3 of the way through the capillary.

Hypoxemia can occur due to:

a. Hypoventilation
b. V/Q mismatch (V – ventilation, Q – perfusion)

c. Shunt (perfusion of an unventilated alveolus, atelectasis, fluid in the alveolus)
d. Diffusion impairments

Hypercarbia can occur due to:
a. Hypoventilation
b. V/Q mismatch
c. Dead space ventilation

Gas Exchange

Hypoventilation and V/Q mismatch are the most common causes of abnormal gas exchange in the PICU.

One can correct hypoventilation by increasing minute ventilation.

One can correct V/Q mismatch by increasing amount of lung that is ventilated or by improving perfusion to those areas that are ventilated.

Pulmonary capillary flow is best at the functional residual capacity (FRC).

Overdistension of alveoli causes compression of capillaries reducing the flow (Q is low, ventilation V is high, so V/Q mismatch approaching dead space ventilation), and lower lung volume (below FRC) also cause kinking of capillaries reducing the capillary flow (Q is relatively low, with unventilated alveoli, blood is shunted).

So, depending on ventilatory pressures (or tidal volumes, PIP, PEEP) and lung perfusion (cardiac output, volume status, PEEP, etc.), these West zones (as discussed earlier) will change, especially during supine or prone positioning.

This leads to the understanding of oxygenation (depending on percentage of shunt) or ventilation (depending on the dead space) and the ventilation of perfused alveoli.

SUMMARY

As evident from above discussion, children are not miniature adults. A knowledge of the physiological differences is important to properly understand the principles of mechanical ventilation in pediatric patients. Respiratory bronchioles, alveolar ducts and alveoli grow in number until 8 years of age, and continue to grow in size until adulthood. Pores of Kohn connecting alveoli are not developed until 1 year of age, and channels of Lambert which connect alveoli to larger airways do not develop until 5 years of age. This results in poor collateral gas circulation in the airways and alveoli. In children, the majority of airway resistance lies in lower airways as compared to adults where nasal passages alone may be responsible for 60 percent of total airway resistance. Furthermore, due to softer cartilage supporting the airway, collapse of the airway is more common with relatively smaller changes of airway pressure. Children have a relatively small functional residual capacity (volume of air in the lungs at the end of normal expiration), and a higher oxygen consumption compared to adults. Therefore, normal children tend to have relatively shallow breaths at a rate higher than adults. When a child is in respiratory

distress, the respiratory rate increases ultimately progressing to slowing respirations, progressing to gasping followed by apnea or cardio respiratory arrest. It is therefore, extremely important to recognize tachypnea, agitation, nasal flaring, grunting, retractions as early signs of hypoxemia and respiratory failure. Cyanosis, lethargy and bradycardia are late signs dangerously close to cardiorespiratory arrest. This must and can be avoided by early recognition and appropriate intervention.

FURTHER READINGS

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2. West JB. Respiratory Physiology the Essentials 1979, Williams and Wilkins (Baltimore).

3 Chapter

Oxygen Therapy

Satish Deopujari, Suchitra Ranjit

Oxygen therapy is the most important aspect of supportive care in the management of a critically ill child. Knowledge of the physiology of oxygenation is a key to the proper oxygen therapy. High flow systems are more dependable devices for oxygenation and their use needs to be stressed.

Patients on oxygen need close monitoring. Ventilatory support and CPAP is mandatory in some patients in addition to oxygen therapy for the prevention and treatment of hypoxia.

Oxygen is one of the most essential elements in the body but surprisingly there are no stores of oxygen (there is no physiological explanation to this fact). One molecule of glucose yields 32 molecules of ATP in presence of oxygen but the same glucose yields only 2 molecules of ATP in its absence and in addition yields lactic acid.

DEFINITION

Increasing the concentration of oxygen in the inspired air to correct or prevent hypoxia is oxygen therapy.[1]

Arterial oxygen tension (PaO_2) of less than 60 mm Hg beyond the age of 28 days of life is defined as Hypoxemia. Hypoxemia in neonates is defined as PaO_2 of less than 50 mm Hg.[2]

PHYSIOLOGY

Knowledge of physiology of oxygenation is important for proper oxygen therapy. The concept of partial pressure, saturation and content of oxygen is dealt with in the lines to come.

Partial Pressure of Oxygen

Atmospheric pressure at sea level is 760 mm Hg. Oxygen constitutes 21 percent of air and thus the partial pressure of oxygen is around 160 mm Hg at sea level (21% of 760 mm Hg). Partial pressure of oxygen in the alveoli PAO_2 (note the capital A) is 110 mm Hg. Oxygen is inhaled from the environment into the alveoli and from there to blood and tissues depending on its partial pressure.

For all the practical purposes, partial pressure of oxygen in the alveoli can be calculated as:

$$PAO_2 = FiO_2 (P_B\text{-}47) - 1.2 (PaCO_2)$$

P_B = Barometric pressure, 47 = water vapor pressure

Partial pressure of oxygen is important for:

1. Driving oxygen from the environment to the mitochondria (Driving pressure)
2. The saturation of hemoglobin.

The partial pressure of oxygen in arterial blood (PaO_2, note the small 'a') is measured by a blood gas machine. Oxygen molecules dissolved in plasma (i.e. not bound to hemoglobin) are free to impinge on the measuring oxygen electrode. These free oxygen molecules are noted as the partial pressure of oxygen. PaO_2 is a function of the alveolar PO_2 and the alveolar-capillary interface. Arterial PaO_2 (small 'a') gives us valuable information about the status of gas exchange within the lungs, provided it is subtracted from the calculated alveolar PAO_2 (note the capital 'A').

Saturation of hemoglobin is measured by pulse oxymeter (SpO_2). An instrument known as co-oximeter can directly measure the saturation of arterial hemoglobin, an *in vitro* measurement called as SaO_2. Saturation of hemoglobin depends on the partial pressure of oxygen. The relationship between the saturation and PaO_2 is not linear but S shaped and is known as the oxygen dissociation curve. The curve denotes that when the PaO_2 falls below 60 mm Hg hemoglobin saturation rapidly declines and thus, it is imperative to maintain saturation above 90 percent (Fig. 3.1). The concept of saturation of hemoglobin and partial pressure can be compared to a transport bus. The seats in the bus are analogous to hemoglobin and the oxygen to passengers. If the bus has 12 (12 gm Hb / 100 ml of blood) seats and all seats are occupied, the saturation is 100 percent. With bus having only 7 seats and all seats are occupied the saturation is still 100 percent but

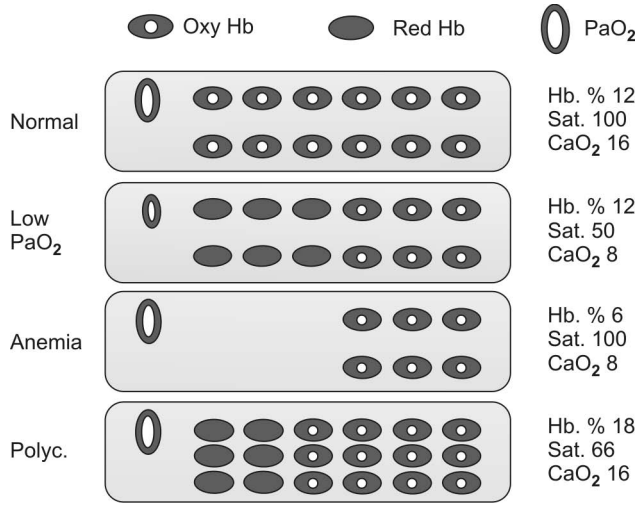


Fig. 3.1: Effect of PaO_2, Hb concentration, oxyhemoglobin saturation on oxygen content (CaO_2) in different conditions. Polyc. (Polycythemia)
$CaO_2 = (Hb. \times 1.34 \times SaO_2) + (PaO_2 \times .003 ml)$

the number of passengers in this bus are less, a situation akin to anemia. In a patient with hemoglobin of 6 gm percent and if all this hemoglobin is to carry oxygen, the pulse oximeter will show a saturation of 100% but the amount of oxygen per 100 ml of blood is obviously less. With a low PaO_2, hemoglobin carries less oxygen and the saturation is less, depending on the oxygen dissociation curve. In patients with polycythemia, the situation is like a bus with more number of seats say 18, even if 80% of these seats are occupied, there will be enough oxygen in the blood. Remember the only person who will take the bus from one place to the other is the driver (The PaO_2).

Content of Oxygen in the Blood

The amount of oxygen carried by the hemoglobin can be calculated or actually measured and is determined mainly by the saturation and the amount of hemoglobin. Normally, 100 ml of blood contains 16 to 20 ml of oxygen and is a prime indicator of hypoxemia. Content of oxygen (CaO_2) is calculated by the following formula:

$$CaO_2 = (Hb. \times 1.34 \times SaO_2) + (PaO_2 \times .003 \text{ ml})$$

where, $(Hb. \times 1.34 \times SaO_2)$ = Oxygen bound to hemoglobin

$(PaO_2 \times .003 \text{ ml})$ = Oxygen dissolved in plasma

As was mentioned earlier, patient with severe anemia will have less amount of oxygen for a given amount of saturation. Content of oxygen for hemoglobin of 15 gm percent and 10 gm percent is shown in Figure 3.2. Oxygen transport to the tissues occurs in two ways: Either dissolved in plasma (PaO_2) or bound to hemoglobin molecules (SaO_2). The relationship between SaO_2 and PaO_2 is the oxygen dissociation curve.

Most of the oxygen is carried in the blood bound to hemoglobin (98.5%). Once the hemoglobin is fully saturated, increasing the PaO_2 will not

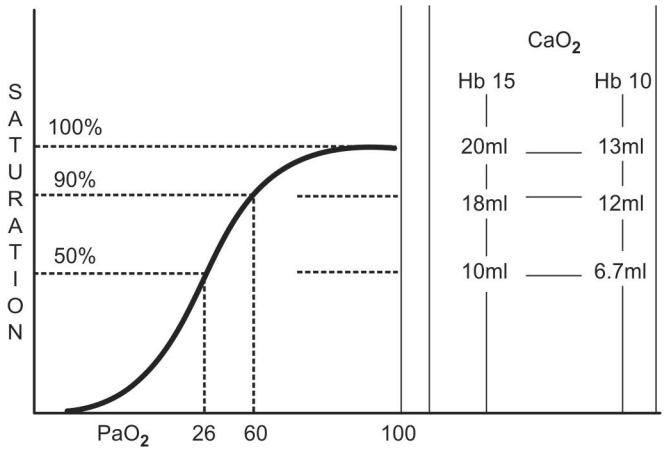


Fig. 3.2: Relationship of hemoglobin, PaO_2, saturation and oxygen content (CaO_2)

significantly increase the content of oxygen in blood as it will only increase the amount of dissolved oxygen.

Hypoxemia and Hypoxia

Reduced oxygen content of the blood is hypoxemia; whereas impaired oxygen utilization by the tissues is hypoxia. It is possible to have hypoxia inspite of normal amount of oxygen in the blood and the reverse is also true.

The goal of proper oxygenation is the adequate supply of oxygen to the tissues. Supply of oxygen to the tissues is a combined function of the content of oxygen in blood and that of cardiac output. Patients with anemia carry less amount of oxygen in blood but are not always necessarily hypoxic because the delivery of oxygen to the tissues is achieved by increasing the cardiac output.

Recognition of Hypoxia

Oxygen delivery to tissues depends on the adequate ventilation, gas exchange, and circulation (Fig. 3.3). Tissue hypoxia occurs within 4 minutes of failure of any of these systems.

The successful treatment of tissue hypoxia requires early recognition. This is difficult since the clinical features are often nonspecific and include altered mental state, dyspnea, cyanosis, tachypnea, arrhythmias, and coma.

Central cyanosis is an unreliable indicator of tissue hypoxia (It is detectable when the concentration of reduced hemoglobin is about 1.5 gm / 100 ml of blood rather than the widely quoted value of 5 gm / 100 ml of blood).[3]

The causes of tissue hypoxia can be grouped into two broad categories:

1. Those causing arterial hypoxemia.
2. Those causing failure of the oxygen-transport system without arterial hypoxemia.

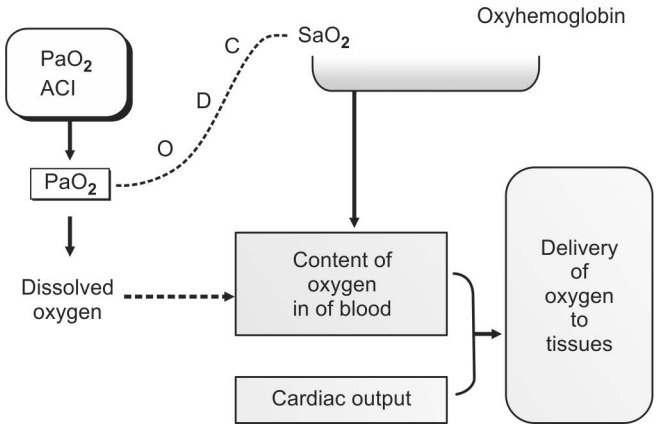


Fig. 3.3: Factors affecting oxygen delivery ACI (Alveolar capillary interface), ODC (Oxygen dissociation curve)

Hemoglobin saturation as measured by pulse oximeter (SpO_2) and PaO_2 (Measured by blood gas machine) are readily measured parameters and remain the principal indicators for initiating, monitoring, and adjusting oxygen therapy. However, PaO_2 and SpO_2 can be normal when tissue hypoxia is caused by the low output cardiac states, anemia, and failure of tissues to utilize oxygen.

Types of Hypoxemia

Type A is characterized by low oxygen tension in alveoli (PAO_2). A low PAO_2 can result from:

1. Low barometric pressure
2. Low fraction of inspired oxygen (FiO_2)
3. Hypercarbia—elevated partial pressure of carbon dioxide in the arterial blood ($PaCO_2$).

Low barometric pressure occurs at high altitudes. Low FiO_2 is rarely a problem, since inspired air is nearly always composed of 21 percent oxygen and 79 percent nitrogen. Even at the top of the Mount Everest, FiO_2 is normal (21%), it is the barometric pressure that is low.

Type B is characterized by an elevated alveolar-arterial oxygen tension gradient (AaG). The AaG is the difference between the PAO_2, as computed from the alveolar gas equation, and the PaO_2, as obtained from the arterial blood gas analysis.

$$AaG = PAO_2 - PaO_2$$

AaG is a useful index of oxygen exchange in the lung. In a normal individual breathing room air, AaG is 10 mm Hg. AaG varies with FiO_2. Causes of elevated AaG are:

1. Ventilation / perfusion mismatch
2. Pulmonary or cardiac shunt
3. Decreased mixed venous oxygen saturation.

Oxygen Delivery Devices

Oxygen is a drug and should be prescribed in proper doses, with proper mode of delivery and needs to be monitored while being administered. The administration of oxygen to the patients requires the selection of an oxygen delivery system that suits the patient's size, needs, and the therapeutic goals. Oxygen delivery systems are essentially categorized as either *low-flow or high-flow systems.*

1. *A low-flow system* provides an FiO_2 that varies with the patient's inspiratory flow.
2. *A high-flow system* provides a specific FiO_2 at flows that meet or exceed the patient's inspiratory flow requirement.

The patient's actual flow requirement depends on his minute ventilation and his I:E ratio.[2]

- Normal flow requirements are three to four times the minute ventilation.
- Minute Ventilation = Tidal Volume × Respiratory Rate.
- Normal tidal volume is around 6 ml / kg.

- Thus, a 10 kg child breathing 60 times a minute with an assumed I:E ratio of 1:2 (his minute ventilation will be 3.6 L / min) needs around 12 L / min of oxygen or air-oxygen mixture.
- Some of the commonly used devices for oxygen delivery are discussed below.

Nasal cannula consists of two soft prongs that arise from the oxygen supply tubing. The prongs are inserted into the patient's nares, and the tubing is secured to the patient's face. Oxygen flows from the cannula into the patient's nasopharynx, which acts as an anatomical reservoir. The fractional concentration of inspired oxygen (FiO_2) varies with the patient's inspiratory flow. In a newborn baby, nasal cannula delivers 24 to 45 percent FiO_2. Flowmeters capable of delivering 0.125 L / min are effective in achieving a concentration of approximately 28 to 30 percent.[4-6]

Maximum flow accepted through a nasal cannula is 2 L / min and the humidification of oxygen is not necessary for this flow.[5]

Improper size cannula can lead to nasal obstruction or irritation. Inadvertent CPAP may be administered depending upon the size of the nasal cannula and the rate of gas flow.

Nasopharyngeal catheters are soft tubes with several distal holes. The catheter should be inserted into the patient's nose to a depth, slightly above the uvula. Oxygen flows from the catheter into the patient's oropharynx, which acts as an anatomical reservoir. The FiO_2 varies with the patient's inspiratory flow.

Improper insertion can cause nasal or pharyngeal trauma. Excessive flow can produce pain in the frontal sinuses. Excessive secretions and / or mucosal inflammation can result in occlusion of distal openings.

Simple oxygen masks are plastic reservoirs designed to fit over the patient's nose and mouth and can be secured around the patient's head by an elastic strap. A reservoir effect is produced by the internal capacity of the mask. Holes on each side of the mask provide an egress for exhaled gases and serve as room-air entrainment ports. The FiO_2 varies with the patient's inspiratory flow.

Aspiration of vomitus may be more likely when a mask is in the place. Rebreathing may result in accumulation of CO_2 if O_2 flow is inadequate.

Partial-rebreathing masks are similar to simple oxygen masks but contain a reservoir at the base of the mask. The reservoir receives fresh gas plus exhaled gas approximately equal to the volume of the patient's anatomical dead space. The oxygen concentration of the exhaled gases combined with the supply of fresh oxygen, permits the use of flows lower than those necessary for other devices (e.g., non-rebreathing masks), and potentially conserves oxygen use.[5]

Non-rebreathing masks are similar to partial-rebreathing masks but they do not permit the mixing of exhaled gases with the fresh gas supply. A series of one-way valves placed at the reservoir opening and on the side ports ensures a fresh oxygen supply with minimal dilution from the entrainment

TABLE 3.1: Determining oxygen percentages by various devices

	Liters	*Nasal cannula*	*Simple mask*	*Partial rebreather mask*	*Non-rebreather mask*
	2	23 to 28%	Not applicable	Not applicable	Not applicable
	3	28 to 30%	— do—	— do—	— do—
	4	Not applicable	— do—	— do—	— do—
Oxygen	5	— do—	40%	— do—	— do—
delivery	6	— do—	45 to 50%	35%	55 to 60%
rate (liters/	8	— do—	Not applicable	45 to 50%	60 to 80%
min)	10	— do—	— do—	60%	80 to 90%
	12	— do—	— do—	60%	90%
	15	— do—	— do—	60%	90%

of room air. This design provides a higher FiO_2 than the simple and partial-rebreathing masks. Table 3.1 gives information for the FiO_2 achieved by various devices.

Oxygen hood: Oxygen hood is a common method of administering oxygen to neonates and infants. Most hoods need a flow of around 7 L / min.[5] The FiO_2 achieved inside the hood varies from 22 to 90 percent and depends on the flow rate of oxygen, babies' respiratory needs, the shape of the hood and the size of the side port openings. When high flows are used, a layering effect may occur, with the highest oxygen concentrations settling towards the bottom, for this reason oxygen analyzer sensor should be placed as near to the face of the baby as possible. It is important to maintain adequate heat and humidity inside the hood. Oxygen hoods can be fed through a venturi system so that the FiO_2 inside remains fixed. There is some concern about the noise level inside the hood and the issue is not settled as yet.

An Air-entrainment Mask/Venturi Mask

Venturi valves were designed by Campbell in 1960 and are available for 24 to 60 percent oxygen concentrations. This is the best and economical solution to the problem of oxygenation and most of our patients need to be on this high flow device for their oxygen needs. Oxygen flows through the narrowed orifice creating a jet effect. Air is entrained through the side ports where it blends with the oxygen, delivering the correct concentration of air- oxygen mixture to the mask (Fig. 3.4). Venturi masks may not require humidification because Venturi entrains a much greater flow of room air compared to the oxygen resulting in the delivery of essentially room air humidity.[6] Most patients need air-oxygen mixture for correcting hypoxia and not 100 percent oxygen. Venturi valves deliver air-oxygen mixture at high flow rates, the ratio of which will not vary at any point of time and thus, fixed FiO_2 is delivered to the patient. Where FiO_2 meters are not available, Venturi valves give the best option to monitor the patient as far as the need for oxygenation is concerned. If a given child was maintaining good saturation on a Venturi valve of 50 percent FiO_2 and now he accepts

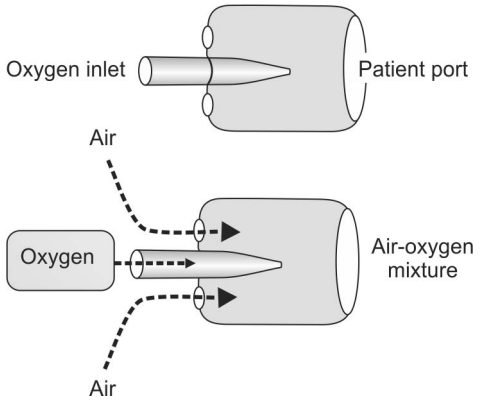


Fig. 3.4: Venturi principle for air entrainment

TABLE 3.2: Venturi mask: flows and entrainment ratios

Oxygen conc	*Total (LMP)*	*Oxygen flow rate (LMP)*	*Approx. Air: Oxygen ratio*
24%	53	2	25:1
28%	45	4	10:1
31%	47	6	7:1
35%	45	8	5:1
40%	33	8	3:1
50%	32	12	5:3
60%	30	15	1:1

a venturi of 40 percent and still maintains a good saturation, the child is likely to be recovering from the illness. Table 3.2 gives details of various Venturi valves.

The Advantages of using a Venturi:

1. A high flow device guarantees the delivery of fixed FiO_2.
2. Can be used in patients with hypoxic drive dependent respiration.
3. Helps in monitoring the patient (Whether the patient is improving or otherwise).
4. Warning signal (patient needing 60% FiO_2 may need ventilatory support).
5. Humidification may not be necessary.
6. Economical and reliable.

CPAP (Continuous positive airway pressure)

Indicated as a possible device for correcting Hypoxemia in patients with PaO_2 less than 60 mm Hg on FiO_2 of 60 percent with normal ventilatory activity (Normal $PaCO_2$). Full discussion on CPAP is beyond the scope of this chapter.

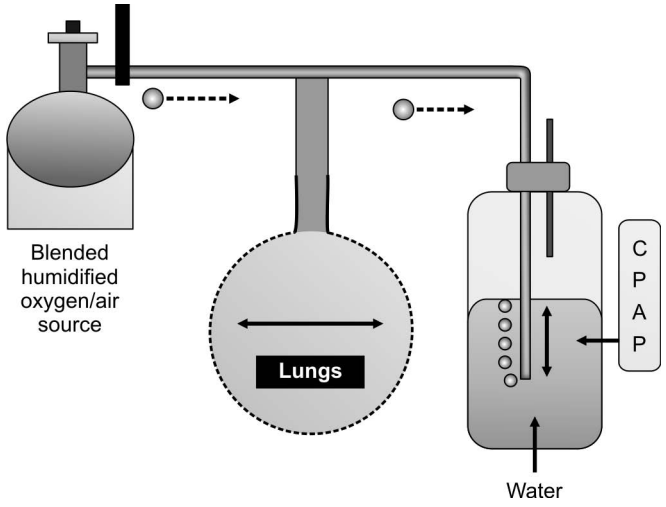


Fig. 3.5: Schematic diagram of CPAP delivery system

CPAP improves oxygenation by:

1. Increasing the FRC of lungs and thus reducing the work of breathing.
2. Increasing static compliance of lung.[7,8]
3. Recruiting the alveoli for airway exchange.
4. Improving ventilation perfusion relationship.

CPAP or PEEP (Intubated patient) partially obstructs exhalation and thus keep the lungs expanded during expiration (Prevents the total collapse of lung at the end of expiration). It is easy to expand a partially collapsed lung than a lung, which is completely collapsed. Especially in early infancy and in neonates, there is a natural tendency of lungs to collapse and hence the benefit of CPAP (Fig. 3.5).

CPAP can be given:

1. Without Intubation
   a. Nasal prongs
   b. Nasopharyngeal catheters
   c. Tightly fitting mask.
2. With Intubation
   a. With ventilator
   b. Without ventilator.

Patients on CPAP need to be observed closely as patients on ventilators and especially for:

1. Air leak syndrome
2. Ventilatory failure
3. Decrease in peripheral circulation
4. Sudden loss of CPAP
5. Respiratory drive.

CPAP can be delivered by various means. These devices partially obstruct the expiratory flow and thus prevent the complete collapse of lung at the end of expiration. Simple device can be made from a bottle with a glass tube immersed in it for the intended depth to deliver the desired CPAP.

Patient is weaned from CPAP at a point when he maintains adequate saturation on FiO_2 of 30 percent. First the CPAP is reduced slowly and then the reduction in FiO_2 follows.

Oxygen concentrator: Oxygen concentrator separates the oxygen from the nitrogen in the air by a method using absorption and desorption. Air from the environment passes through the compressor and then through the zeolite, a material that under high pressure absorbs nitrogen. Oxygen on the contrary passes straight through this material.

The outlet pressure of the concentrator is only 5 PSI as compared to the outlet pressure of standard oxygen cylinder, which is 50 PSI. The low output pressure of the concentrator means that the FiO_2 delivered by the concentrator though states a value of 90 percent, in comparison to the standard oxygen cylinder output, the value would not be more than 40 percent even 40 percent. FiO_2 is good enough in most situations.

The Principles of Oxygenation

The goal of oxygenation is the consumption of oxygen by the tissues, and to that effect there is no single parameter which can be totally relied upon. Complete assessment of a patient including the clinical examination, pulse oximetric saturation, blood gases, temporal change in the status of blood gases, gastric tonometry and evidence of anaerobic metabolism are some of the parameters on which the status of oxygenation is assessed. To achieve the optimum level of oxygen in the blood with a minimum possible FiO_2 is the essence of proper oxygenation. Feedback loop for changing FiO_2, adding CPAP or initiating ventilation comes from the data obtained from clinical examination, blood gas values and pulse oxymetric saturation (Fig. 3.6).

Initiation

Initiation of oxygenation should be done without wasting time and with a thought that one can always withdraw oxygen when the need is not felt. Starting FiO_2 should be high in most of the situations but need not be 100 percent. It is preferable to start with FiO_2 of 40 to 60 percent, using a high flow device.

In most of the situations, one need not use 100 percent oxygen, it is indicated only for the following two situations:

1. Resuscitation
2. Transport.

Maintenance

Once the patient is stabilized, maintenance therapy is instituted depending on the following principles:

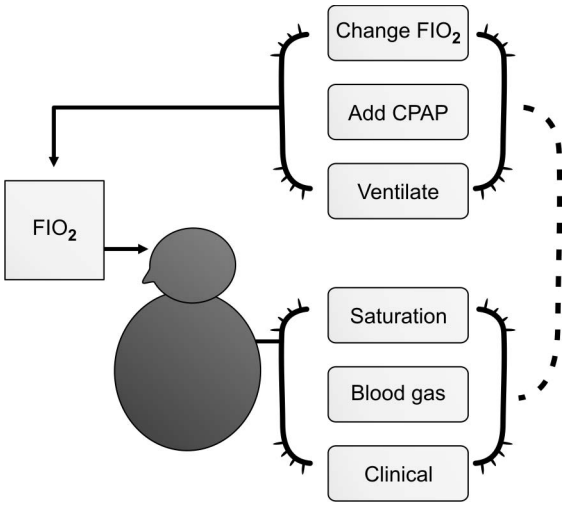


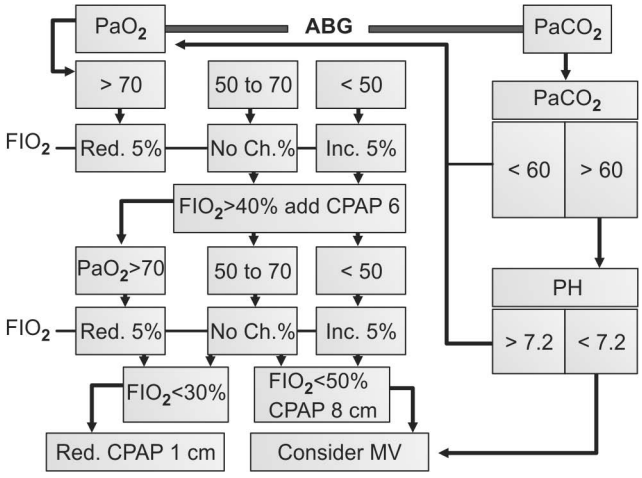
Fig. 3.6: Feedback loop for changing FIO_2 institution of CPAP and ventilation

1. Patient should be on high flow system till the time he is in stable cardiorespiratory state.
2. Minimum FiO_2 should be used to maintain the saturation of 92 percent and above.
3. No single investigation or monitoring modality is confirmatory of hypoxia.
4. Avoid fluctuations in FiO_2.
5. Patient should be nursed in a comfortable environment. The position of patient should ensure patency of airways
   - Lateral nursing
   - Patient who is looking towards heaven is likely to go there.
6. Rarely one needs 100 percent oxygen, if required it should never be denied for the fear of toxicity.
7. Close monitoring of all patients is mandatory. It is desirable to use continuous pulse oxymetry.
8. Withdrawal of oxygen support is a decision based on laboratory parameters and clinical situations. It is desirable to consider weaning for patients who are stable with FiO_2 of 30 percent.
9. Newborn babies need closer monitoring for hyperoxia. High-risk babies need to have their saturation maintained between 90 to 94 percent.

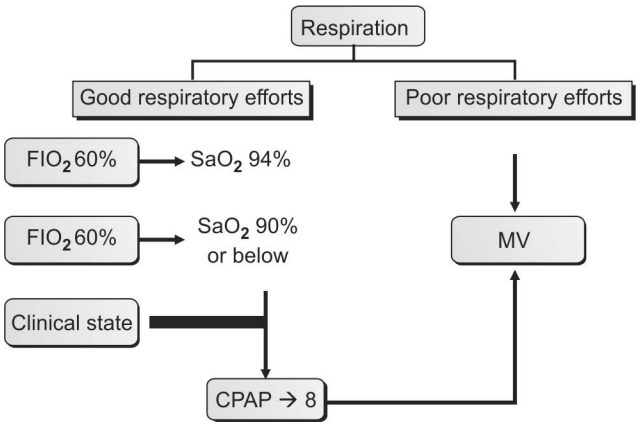
Flow chart 3.1 is an excellent guide for an ideal set-up with facilities for blood gas and FiO_2 monitoring.[8] These facilities are often not available, and hence an alternative strategy is suggested knowing fully well the limitations involved (Flow chart 3.2).

Patients who are not in a position to maintain adequate oxygenation on FiO_2 of 60 percent with CPAP of 8 cm of water, are potential candidates

Flow chart 3.1: Manipulation of FIO_2, use of CPAP and MV



Flow chart 3.2: Simple clinical algorithm for respiratory support. CPAP and MV



for mechanical ventilation. Indications for mechanical ventilation are based on laboratory parameters and clinical condition of the patient.

Oxygen Toxicity

The risk of oxygen toxicity is well documented and can be broadly classified in two categories:

A. Related to high FiO_2
B. Related to high PaO_2.

The most important complications are:

1. Retinopathy of prematurity
2. Hypoventilation

3. Absorption atelectasis
4. Bronchopulmonary dysplasia.

What PaO_2 and FiO_2 is Safe?

It is currently estimated that 20 percent of all infants weighing less than 1500 gm develop evidence of retinopathy.[10] Thus, it is advisable to keep the SpO_2 of high-risk babies between 90 to 94 percent. The most important aspect in the management of ROP is early screening of these babies. American Academy of Pediatrics recommends screening of infants less than 36 weeks gestation, those babies weighing less than 2000 gm and received oxygen and infants less than 1000 gm at birth even if they have not received oxygen.[9-11]

An infant who requires oxygen at 1 week of age but is still oxygen dependent at 28 days of age is defined as having BPD. BPD develops in 15 to 38 percent of all infants weighing less than 1500 gm who received mechanical ventilation.[12,13]

It is preferable to use as less FiO_2 as possible and for a short period to maintain adequate oxygenation. FiO_2 above 60 percent is known to be toxic. In patients with chronic lung disease, there is a danger of oxygen induced hypoventilation and in these patients it is desirable to use controlled oxygenation with Venturi valves. One must at the same time remember that in life saving situation no amount of oxygen is considered undesirable.

CONCLUSION

Oxygen is a life-saving drug. As there are no stores for oxygen, the rapidity with which the treatment is instituted is an important factor that determines the overall prognosis of a patient. As with any other drug there are side effects of oxygen but it should never be withheld for the fear of toxicity. Patients on oxygen need close monitoring similar to patients on ventilators. Optimum oxygenation is the best, hyperoxia is bad, but hypoxia is worst.

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4 Chapter

Basic Mechanical Ventilation

Praveen Khilnani, Deepika Singhal

INTRODUCTION

Mechanical ventilation in children and neonates is different from adults.

While basic priciples of Physics and gas flow apply to all age groups, anatomical and physiological differences play a significant role in selecting the type of ventilator as well as the ventilatory modes and settings.

Upper airway in children is cephalad, funnel shaped with narrowest area being subglottic (at the level of cricoid ring), as compared to adults where the upper airway is tubular with narrowest part at the vocal cords.[1] Airway resistance increases inversely by 4th power of radius; i.e. in an already small airway even one mm of edema or secretions will increase the airway resistance and turbulent flow markedly necessitating treatment of airway edema, suctioning of secretion, measures to control secretions. Low functional residual capacity (FRC: Volume of air in the lungs at the end of expiration) reduces the oxygen reserve, reduces the time that apnea can be allowed in a child.

Respirations are shallow and rapid due to predominant diaphragmatic breathing, and inadequate chest expansion due to inadequate costo-vertebral bucket handle movement in children. Therefore, a child tends to get tachypneic rather than increasing the depth of respiration in response to hypoxemia. Oxygen consumption / kg body weight is higher, therefore, tolerance to hypoxemia is lower.

Susceptibility to bradycardia in response to hypoxemia is also higher due to high vagal tone. Pores of Kohn and channels of Lambert (broncho alveolar and interalveolar collaterals) are inadequately developed making regional atelectasis more frequent.[2] Closing volumes are lower and airway collapse due to inadequate strength of the cartilage in the airways is common, making a child particularly susceptible to laryngomalacia, and tracheobronchomalacia as well as lower airways closure.

Therefore, children tend to require smaller tidal volumes, faster respiratory rates, adequate size uncuffed endotrachel tube, adequately suctioned clear airway for proper management of mechanical ventilation. Other important factors for choosing the ventilatory setting include the primary pathology, i.e. asthma, ARDS, pneumonia, airleak syndrome raised intracranial tension, neuromuscular weakness, neonatal hyaline membrane disease, or neonatal persistent pulmonary hypertension (PPHN).

Basic Physiology[3]

Gradient between mouth and pleural space is the driving pressure for the inspired gases, and this gradient is needed to overcome resistance and to maintain alveolus open, by overcoming elastic recoil forces.

Therefore, a balance between elastic recoil of chest wall and the lung determines lung volume at any given time. Normal inspiration is actively initiated by negative intrathoracic pressure driving air into the lungs. Expiration is passive.

Ventilation

Ventilation washes out carbon dioxide from alveoli keeping arterial $PaCO_2$ between 35-45 mm of Hg. Increasing dead space increases the $PaCO_2$.

$$PaCO_2 = k \times \frac{\text{Metabolic production}}{\text{Alveolar minute ventilation}}$$

Alveolar MV = respiratory rate x effective tidal volume
Effective TV = TV – dead space
Dead Space = Anatomic (nose, pharynx, trachea, bronchi) + Physiologic (alveoli that are ventilated but not perfused)

Adequate minute ventilation is essential to keep $PaCO_2$ within normal limits.

Oxygenation

Partial pressure of oxygen in alveolus (PAO_2) is the driving pressure for gas exchange across the alveolar-capillary barrier determining oxygenation.
$PAO_2 = (\{\text{Atmospheric pressure} - \text{water vapor}\} \times FiO_2) - PaCO_2/RQ$
RQ = respiratory quotient

Adequate perfusion to alveoli that are well ventilated improves oxygenation.

Hemoglobin is fully saturated 1/3 of the way through the capillary.

Hypoxemia can occur due to:
a. Hypoventilation
b. V/Q mismatch (V- ventilation, Q- perfusion)
c. Shunt (Perfusion of an unventilated alveolus, atelectasis, fluid in the alveous)
d. Diffusion impairments.

Hypercarbia can occur due to:
a. Hypoventilation
b. V/Q mismatch
c. Dead space ventilation.

Gas Exchange

Hypoventilation and V/Q mismatch are the most common causes of abnormal gas exchange in the PICU.

One can correct hypoventilation by increasing minute ventilation.

One can correct V/Q mismatch by increasing amount of lung that is ventilated or by improving perfusion to those areas that are ventilated.

Time Constant

Time constant is the time required to fill an alveolar space. It depends on the resistance and compliance. In pediatric age group, one time constant that fills an alveolar unit to 63 percent of its capacity is 0.15 seconds. It takes three time constants to achieve greater than 90 percent capacity of the alveolar unit filled.

Time constant = Resistance x Compliance

This signifies that a certain minimum inspiratory time is required to fill the alveoli adequately which is generally two to three time constants, i.e. 0.3 to 0.45 seconds. This is important when selecting the inspiratory time on the conventional ventilator.

INDICATIONS OF MECHANICAL VENTILATION[4] (FLOW CHART 4.1)

Indications remain essentially clinical may not be always substantiated by objective lab parameters such as blood gas analysis.
Common indications include:

1. Respiratory Failure
   a. Apnea / Respiratory Arrest
   b. Inadequate ventilation
   c. Inadequate oxygenation
   d. Chronic respiratory insufficiency with failure to thrive.
2. Cardiac Insufficiency / Shock
   a. Eliminate work of breathing
   b. Reduce oxygen consumption.
3. Neurologic dysfunction
   a. Central hypoventilation / frequent apnea
   b. Patient comatose, GCS (Glasgow Coma Score) ≤ 8
   c. Inability to protect airway.

Commonly used Nomenclature

- Airway pressures
- Peak inspiratory pressure (PIP)
- Positive end expiratory pressure (PEEP)
- Pressure above peep (PAP)
- Mean airway pressure (MAP).

Continuous Positive Airway Pressure (CPAP)

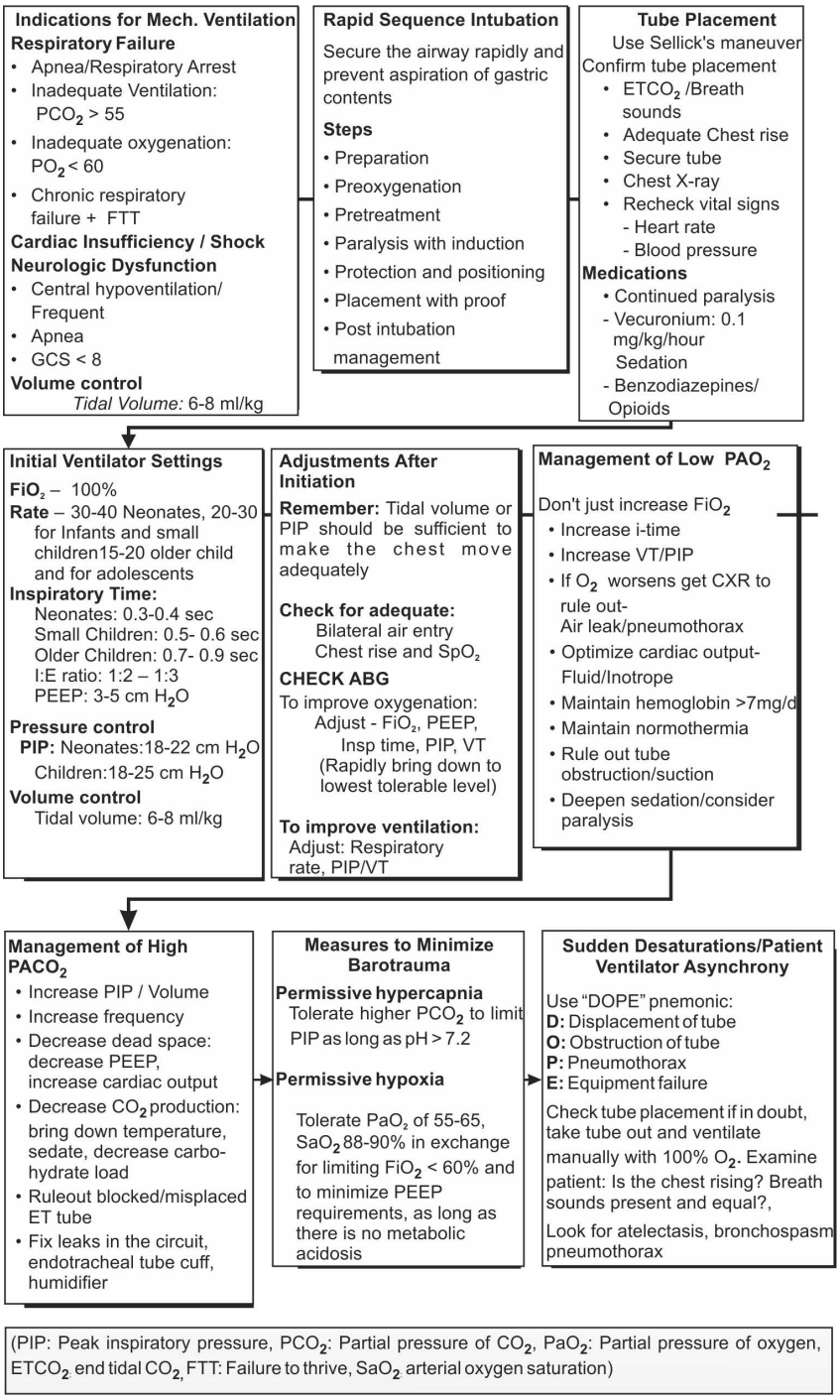
- Inspiratory time or I:E ratio
- Frequency(f): Ventilatory rate
- Tidal volume (Vt): Amount of gas delivered with each breath.

Modes of Ventilation

Control Modes

In this mode, every breath is fully supported by the ventilator. In classic control modes, patients were unable to breathe except at the controlled set

Flow chart 4.1: Basic mechanical ventilation



(PIP: Peak inspiratory pressure, PCO_2: Partial pressure of CO_2, PaO_2: Partial pressure of oxygen, $ETCO_2$ end tidal CO_2, FTT: Failure to thrive, SaO_2 arterial oxygen saturation)

rate. In a conventional controlled mode, weaning is not possible by decreasing rate, patient may hyperventilate if agitated leading to patient / ventilator asynchrony. Patients on control modes will need sedation and / or paralysis with a muscle relaxant. In newer control modes, machines may act in assist-control, with a minimum set rate and all triggered breaths above that rate are also fully supported.

IMV Modes

Intermittent mandatory ventilation modes. In this mode breaths "above" set rate are not supported. Most modern ventilators have synchronized intermittent mandatory ventilation (SIMV)

SIMV: Ventilator Synchronizes IMV "Breath" with Patient's Effort

Patient takes "own" breaths in between (with or without pressure support) the set SIMV rate. There is a potential for increased work of breathing and patient / ventilator asynchrony, if the trigger sensitivity set on the ventilator is too low, requiring patient to generate higher negative inspiratory force to trigger a supported breath.

A/C Assist Control Mode

Triggered by patients inspiratory effort, ventilator delivers preset volume or pressure. A minimum backup rate has to be set on the ventilator otherwise ventilator will not cycle if patient has apnea.

Support Mode

If patient has tachypnea then in A / C mode hyperventilation and hypocapnea may occur.

Pressure Support[5]

Ventilator supplies pressure support (flow) at a preset level but rate is determined by the patient, expiration begins passively when inspiratory flow decreases below a certain level preset in the ventilator (flow cycled); Volume support is also available in Servo 300 ventilators following the principle of pressure suport delivery of the set volume over the patient's natural inspiratory time duration keeping the pressure to a minimum.

Pressure support can decrease work of breathing by providing flow during inspiration for patient triggered breaths. It can be given with spontaneous breaths in IMV modes or as stand alone mode without set rate, as well as for weaning to retain coordination of respiratory muscles in patients on ventilation for longer than few weeks.

BASIC FUNDAMENTALS OF VENTILATION

Ventilators deliver gas to the lungs using positive pressure at a certain rate. The amount of gas delivered can be *limited* by time, pressure or volume. The duration can be *cycled* by time, pressure or flow.

If volume is set, pressure varies; if pressure is set, volume varies according to the compliance.

Compliance = $\delta_{volume} / \delta_{pressure}$

Chest must rise no matter which mode is chosen.

Following are the three main expectations from the ventilator:

1. Ventilator must recognize patient's respiratory efforts (trigger).
2. Ventilator must be able to meet patient's demands (response).
3. Ventilator must not interfere with patient's efforts (synchrony).

Whenever a breath is supported by the ventilator, regardless of the mode, the limit of the support is determined by a preset pressure or volume.

Volume limited: Preset tidal volume

Pressure limited: Preset PIP.

Pressure vs Volume Control[6]

Goal is to ventilate and oxygenate adequately. Both pressure and volume control modes can achieve it. Important requirements include adequate movement of the chest and minimal barotrauma or volutrauma.

One must have a set up of high / low pressure alarms in volume cycling and, low expired tidal volume alarm when using pressure cycling.

Pressure Limited Ventilation (Fig. 4.1)

Ventilator stops the inspiratory cycle when set PIP is achieved.

Caution: Tidal volume changes suddenly as patient's compliance changes. Ventilator delivers a decelerating flow pattern (lower PIP for same Vt)

This can lead to hypoventilation or overexpansion of the lung.

If endotracheal tube is obstructed acutely, delivered tidal volume will decrease. This mode is useful if there is a leak around the endotracheal tube.

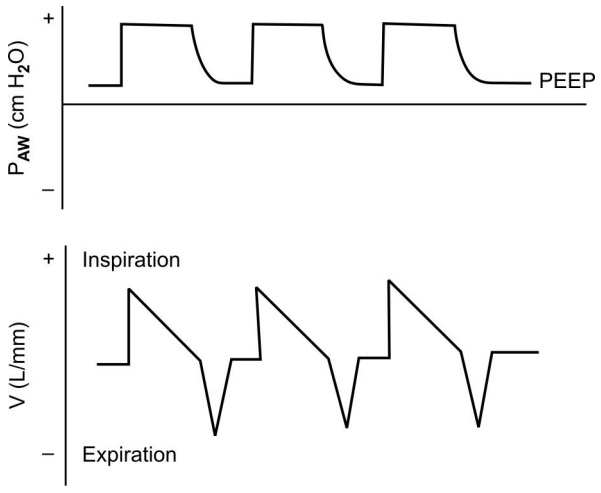


Fig. 4.1: Pressure control ventilation. The ventilator delivers breaths with a preset inspiratory pressure and decelerating flow

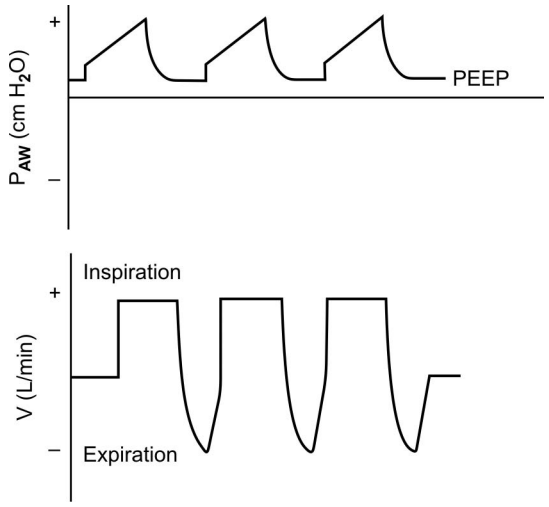


Fig. 4.2: Volume control ventilation. The ventilator delivers the preset tidal volume at a constant flow rate

For improving oxygenation, one needs to control FiO_2 and MAP, (I-time, PIP, PEEP) and to influence ventilation, one needs to control PIP and respiratory rate.

Volume Limited Ventilation (Fig. 4.2)

Ventilator stops the inspiratory cycle when set tidal volume has been delivered.

One can control minute ventilation by changing the tidal volume and rate. For improving oxygenation primarily FiO_2, PEEP, I-time can be manipulated. Increasing tidal volume will also increase the PIP, hence affecting the oxygenation by increasing the mean airway pressure. It delivers volume in a square wave flow pattern. Square wave (constant) flow pattern results in higher PIP for same tidal volume as compared to pressure modes.

Caution: There is no limit *per se* on PIP (so ventilator alarm will have to be set for an upper pressure limit to avoid barotrauma). Volume is lost if there is a circuit leak or significant leak around the endotracheal tube, therefore an expired tidal volume needs to be monitored and set. Some ventilators will alarm automatically if the difference between set inspired tidal volume and expired tidal volume is significant (varies between the ventilators).

Trigger/Sensitivity

Trigger means sensitivity setting of the ventilator. Ventilators have a negative pressure sensor which can be set at various levels of sensitivity to initiate a breath usually based on patient effort (negative pressure) or elapsed time before the next breath in the event of respiratory depression or apnea. The patient's effort can be "sensed" as a change in pressure or a

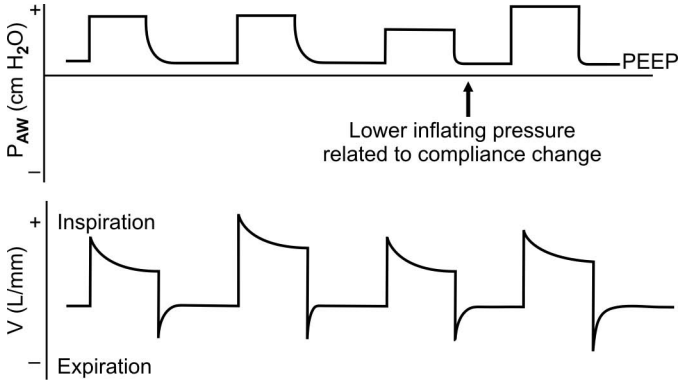


Fig. 4.3: Pressure-regulated volume control. Breaths are delivered at the lowest possible inflating pressure to deliver the preset tidal volume according to the dynamic changes in lung-thorax machanical properties. The pressure is kept constant and inspiratory flow is decelerating

change in flow in the circuit (flow triggering). A setting of greater than 0 makes it too sensitive (meaning the triggered breath from the ventilator will be too frequent). A negative setting (negative 1 or negative 2) setting is usually acceptable. Too much of negative setting will increase the work of the patient (to generate a negative pressure) to trigger a ventilator breath.

Advanced Modes

Pressure-regulated volume control (PRVC)
Volume support
Inverse ratio (IRV) or airway-pressure release ventilation (APRV)
Bilevel positive airway pressure (BIPAP)
High-frequency ventilation / Oscillation

Pressure Regulated Volume Control (PRVC)[7,8] (Fig. 4.3)

It is essentially a control mode, which delivers a set tidal volume with each breath at the lowest possible peak pressure. It delivers the breath with a decelerating flow pattern that is thought to be less injurious to the lung.

Volume support: Volume support is in principle, equivalent to pressure support where a "goal" tidal volume is set and machine delivers that volume at variable pressure support, but within the set limits of pressure support. The machine watches the delivered volumes and adjusts the pressure support to meet desired "goal" within set limits.

Other advanced modes are discussed in Chapter 5 on Advanced ventilation.

Initial Ventilator Settings

One should always have the general idea regarding what initial ventilatory settings to choose when initiating the ventilation. Parameters to choose include:

Rate: Start with a rate that is somewhat normal, i.e. 15 for adolescent / child, 20-30 for infant / small child, 30-40 for a neonate.

FiO_2: 1 (100%) and wean down to level < 0.5.

PEEP: 3-5 cm of H_2O (higher if ARDS, low compliance disease, lower if Asthma, high compliance disease).

Inspiratory time (I-time or I:E ratio): 0.3-0.4 sec for neonates, 0.5-0.6 sec for children, 0.7-0.9 in older children. Normal I:E ratio = 1:2-1:3

Higher I-times may be needed to improve oxygenation in difficult situations (Inverse ratio ventilation) increasing the risk of air leak.

Choose the Mode

Pressure Limited

PIP is set depending upon lung compliance and pathology.
Neonates: 18-22 cm H_2O
Children: 18-25 cm H_2O

Volume Limited

Tidal volume 8 ml / kg.

Adjustments after Initiation

Usually based on blood gases and oxygen saturations

For oxygenation FiO_2, PEEP, i time, PIP (Tidal volume) can be adjusted (increase MAP).

For ventilation Respiratory rate, Tidal volume (in volume limited) and PIP (In pressure limited mode) can be adjusted.

PEEP is used to help prevent alveolar collapse at end inspiration; it can also be used to recruit collapsed lung spaces or to stent open floppy airways.

Gas Exchange Related Problems

Inadequate Oxygenation (Hypoxemia)
Inadequate Ventilation (Hypercarbia).

Inadequate Oxygenation

Important guidelines:

1. Don't just increase FiO_2.
2. Increase tidal volume if volume limited mode, PEEP, inspiratory time (↑ MAP) (Fig. 4.4).
3. Increase peak inspiratory pressure (PIP) / PEEP / inspiratory time (ti) if pressure limited mode (↑ MAP).
4. If O_2 worse, get chest X-ray to rule out air leak(treat!) / if lung fields show worsening (increase PEEP further).
5. Do not forget other measures to improve oxygenation:
   a. Normalize cardiac output (if low output) by fluids and / inotropes
   b. Maintain normal hemoglobin

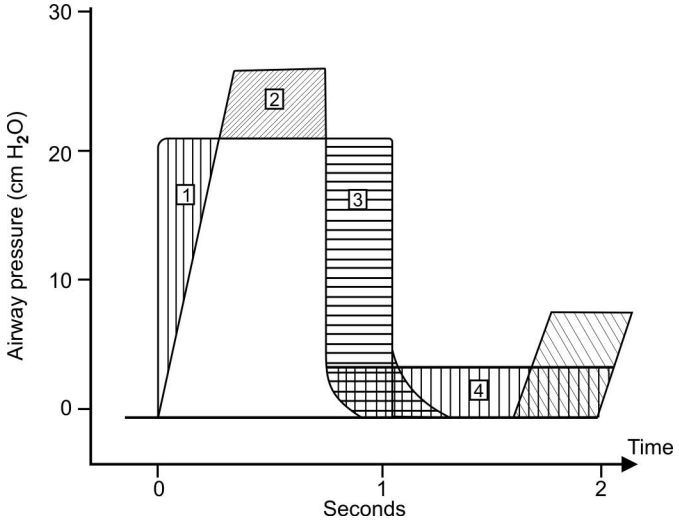


Fig. 4.4: Factors affecting mean airway pressure and oxygention (1) and (3) inspiratory time, (2) peak inspiratory pressure, and (4) positive end expiratory pressure (PEEP)

c. Maintain normothermia
d. Deepen sedation / consider neuromuscular block.

High $PaCO_2$

Common reasons include hypoventilation, deadspace ventilation (too high PEEP, decreased cardiac output, pulmonary vasoconstriction), increased CO_2 production, hyperthermia, high carbohydrate diet, shivering.

Inadequate tidal volume delivery (hypoventilation) will occur with endotracheal tube block, malposition, kink, circuit leak, ventilator malfunction.

Measures for High $PaCO_2$

Guidelines

1. If volume limited: Increase tidal volume (Vt), Increase frequency (rate) (F).
   If asthma: Increase expiratory time, may need to decrease rate to achieve an I:E ratio > 1:3.
2. If pressure limited: Increase peak inspiratory pressure (PIP), decrease PEEP, increase frequency (rate).
3. Decrease dead space (increase cardiac output, decrease PEEP, vasodilator).
4. Decrease CO_2 production: Cool, increase sedation, decrease carbohydrate load.
5. Change endotracheal tube if blocked, kinked, malplaced or out, check proper placement.
6. Fix leaks in the circuit, endotracheal tube cuff, humidifier.

Measures to Reduce Barotrauma and Volutrauma

Following concepts are being increasingly followed in most pediatric intensive care units:

1. **Permissive Hypercapnia**[9]**:** Higher $PaCO_2$ are acceptable in exchange for limiting peak airway pressures: as long as pH > 7.2
2. **Permissive Hypoxemia:** PaO_2 of 55-65; SaO_2 88-90 percent is acceptable in exchange for limiting FiO_2 (<.60) and PEEP, as long as there is no metabolic acidosis.

Adequate oxygen content can be maintained by keeping hematocrit > 30 percent.

Patient ventilator dyssynchrony: Incoordination between the patient and the ventilator: Patient fights the ventilator.

Common causes include: Hypoventilation, hypoxemia, tube block / kink / malposition, bronchospasm, pneumothorax, silent aspiration, increased oxygen demand / increased CO_2 production (in sepsis), inadequate sedation.

If patient fighting the ventilator and desaturating: Immediate measures to be taken:

Use mnemonic: DOPE, D displacement, O obstruction, P pneumothorax, E equipment failure.

1. Check tube placement. When in doubt take the endotracheal tube out, start manual ventilation with 100 percent oxygen.
2. Examine the patient: Is the chest rising? Breath sounds present and equal? Changes in exam? Atelectasis, treat bronchospasm / tube block / malposition / pneumothorax? (Consider needle thoracentesis)
   Examine circulation: Shock? Sepsis?
3. Check arterial blood gas and chest X-ray for worsening lung condition, and for confirming pneumothorax.
4. Examine the ventilator, ventilator circuit / humidifier / gas source.

If there is no other reason for hypoxemia: Increase sedation / muscle relaxation, put back on ventilator.

Sedation and Muscle Relaxation during Ventilation

Most patients can be managed by titration of sedation without muscle relaxation.

Midazolam (0.1-0.2 mg / kg / hr) and vecuronium drip (0.1-0.2 mg / kg / hr) is most commonly used. Morphine or fentanyl drip can also be used if painful procedures are anticipated.

Routine Ventilator Management Protocol

Following protocol is commonly followed:

1. Wean FiO_2 for SpO_2 above 93-94.
2. ABG one hour after intubation, then am-pm schedule (12 hourly), every AM ABG in stable patients, after major ventilator settings change, and 20 minutes after extubation.

3. Pulse oximetry on all patients, End tidal carbon dioxide ($ETCO_2$)/ graphics monitoring if available.
4. Frequent clinical examination for respiratory rate, breath sounds, retractions, color.
5. Chest X-ray every day / alternate day / as needed.

Respiratory Care Protocol

1. Position change 2 hourly right chest tilt / left chest tilt / supine position.
2. Suction 4 hourly and as needed (In line suction to avoid derecruitement / loss of PEEP / desaturation if available).
3. Physiotherapy—8 hourly. Percussion, vibration and postural drainage. NO physiotherapy if labile oxygenation such as ARDS (Acute respiratory distress syndrome), PPHN (persistent pulmonary hypertension of neonate).
4. *Nebulization:* In line nebulization is preferred over manual bagging. Metered dose inhalers (MDIs) can also be used.
5. Disposable circuit change if visible soiling.
6. Humidification / inline disposable humidifier.

Disease Specific Ventilation

Status asthmaticus[10,11] (also see Chapter 11)

- Main Indications are clinical deterioration despite maximal drug therapy.
- Rising $PaCO_2$ (40 to 45 mm) from a low $PaCO_2$ (25 to 30 mm).
- Fatigue, lethargy, deteriorating mental status.
- Mixed respiratory and metabolic acidosis.

Initiation of Ventilation

– For controlled intubation, use sedation and muscle relaxation (short acting muscle relaxant such as succinyl choline.
– Use cuffed endotracheal tube if feasible.
– Ketamine with midazolam are good sedatives for initiation and maintenance of mechanical ventilation.
– Mechanical Ventilation in asthma is associated with high morbidity and mortality.
– Risks involved include barotrauma (air leak) due to dynamic hyperinflation, impaired venous return (tamponade) and low cardiac output due to hyperinflation (pulsus paradoxus). Strategies that minimize end expiratory volume, intrinsic auto peep, and maximize expiratory time, using lower tidal volumes and respiratory rates with permissive hypercapnia have been shown to be associated with lower mortality.

Ventilation Strategies

Controlled Hypoventilation using SIMV or Assist Control

- Volume or pressure limited mode.
- Plateau pressure limit must be < 35 cm water.
- Tidal volume 6-10 ml / kg for 8-14 / min, PEEP 3-4 cm H_2O.

Patient determines frequency rate (f) and inspiratory time (Ti).
Plateau pressure limit set at < 35 cm water.
Tidal vol 6-8 ml/kg.

Patient can determine the respiratory cycle, frequency and flow pattern, there is active exhalation and decreased end expiratory lung volume.

As plateau pressure falls, barotrauma decreases.

Use of PEEP

In conscious patient not on muscle relaxants, on assist control mode, PEEP can be used in physiological levels (3-4 cm H_2O). Application of extrinsic PEEP (at levels less than intrinsic or auto PEEP) helps decrease work of breathing and easier patient triggering. In some ventilators, level of auto PEEP can be monitored.

Controlled Hypercapnia[9]

Both pressure control or volume control can be used as long as plateau pressures do not exceed 35 cm H_2O, rates are at 8 to 14 (I:E ratio 1:3 or more), use of prolonged expiration to avoid intrinsic PEEP and delivered tidal volume 6 to 8 ml/kg. In volume control mode, PIP may go too high. Advantage of Pressure control mode is that decelerating flow delivers volume at a lower inspiratory pressure. Strategies of permissive hypercapnea and permissive hypoxemia are generally acceptable to minimize barotrauma and air leak.

CASE SCENARIO 1

A 10-year-old boy weighing 25 kg comes to the emergency with history of fever and cough for 2 days and has developed respiratory distress for past 3 hours. He is a known case of Bronchial Asthma on regular Fluticasone inhaler but has stopped his inhalers for the past 10 days.

On examination, he is drowsy and lethargic. His heart rate is 130/min, respiratory rate is 40/min with severe intercostal and subcostal retractions with nasal flare. His BP is 100/74 mm Hg, peripheral pulses are feeble and CFT is 4 secs. He is dusky and saturating 84 percent in air which increases to 92 percent in 100 percent oxygen. On auscultation, he has bilateral poor air entry and a chest X-ray done of him reveals bilaterally hyperinflated lung fields. He was immediately intubated and ventilated for impending respiratory failure. He was initiated on PRVC mode of ventilation with the following settings:

1. Tidal volume—150 ml (6 ml/kg)
2. FiO_2—100 percent
3. Rate—12
4. I:E ratio—1:3
5. PEEP—3

His ABG on the above settings was:
pH (7.15), PCO_2 (90), PO_2 (96), HCO_3 (20.1), sat (99%) and BE (–6).

Following this rate was decreased to 8 and FiO_2 to 80 percent such that his I:E ratio increased to 1:4. The repeat ABG revealed a pH of 7.26, PCO_2 72, PO_2 76, HCO_3 23, saturation 96 percent and BE –2. He was continued on the same settings allowing for some permissive hypercapnia as discussed earlier.

Ventilation for Acute Respiratory Distress Syndrome (ARDS) (also see Chapter 10)

Indications for ventilation in ARDS are essentially based on clinical evidence of hypoxemia, and include:

1. Increasing respiratory distress.
2. Tachypnea, tachycardia, accessory muscle use
   (In late stage apnea / bradycardia).
3. Increasing oxygen requirement with desaturation on maximal oxygen.
4. Respiratory fatigue / lethargy.
5. To reduce work of breathing.

Goals of Ventilation in ARDS

Ventilation should be delivered with minimal volutrauma to lungs (using low tidal volumes: 6-8ml / kg),[12] minimal tolerable inspired oxygen with PEEP (positive end expiratory pressure) to achieve PaO_2 of 55 to 80 mm Hg and maximal tolerable arterial PCO_2 (50 to 60 mm Hg) with arterial pH > 7.25 (permissive hypercapnia),[13] and absence of metabolic (hypoxic) acidosis. Conventional ventilation is the most readily available modality. Earlier standard approach used to be: Volume ventilation with tidal volumes 10 to 15 ml / kg with positive end expiratory pressure. Adequate filling pressures with use of fluid and good cardiac contractility with inotropic support to prevent low cardiac output.

Problems with conventional 10 to 15 ml / kg tidal volume and PEEP are as follows:

Barotrauma, volutrauma, air leak (pneumothorax), chronic lung disease, delayed recovery, poor cardiac output, prolonged ventilation and nosocomial infections.

In view of problems with conventional tidal volume ventilation, Low tidal volume strategy is recommended (NIH ARDS Network study).[12]

This was a prospective randomized multicenter trial of 240 patients with two groups using 12 ml / kg vs 6 ml / kg tidal volume, PEEP 5 to 18 cm of H_2O, FiO_2 0.3 to 1, showed 25 percent reduction in mortality in 6 ml / kg group. In another study, use of higher positive end expiratory pressure with lower tidal volumes (Open lung approach)[13,14] has been used with improved results. Gattinoni et al in adults and Marraro in pediatrics ARDS patients, showed that chest CT (computerized tomography) may be useful to see the extent of pulmonary involvement. Gattinoni studied benefits of prone positioning[15] in patients with ARDS with underventilated posterior zones. Prone positioning is being recommended, although transient

improvement in oxygenation occurs but no real effect on improving long term outcomes has been shown. Problems associated with prone positioning include difficulty in nursing management and monitoring (chances of accidental extubation, especially during X-ray examination, and physiotherapy). At authors institution, use of low tidal volume strategy was studied with retrospective controls where 10-15 ml/kg tidal volume was used in children with ARDS showing improvement in oxygenation but no difference in outcomes.[16]

While no good pediatric studies are available on use of prone positioning in ARDS patients and the effect on outcomes, clinical studies are underway on various modalities such as prone positioning, surfactant therapy, high frequency ventilation, nitric oxide and ECMO (see Chapters 17-19).

CASE SCENARIO 2

A 5-year-old, premorbidly well child weighing 15 kg comes to emergency with 3 days of moderate to high grade fever and cough. He has been lethargic for the past 1 day and is not feeding well. Mother noticed that he is breathing fast since morning and has become dusky and unresponsive for the past 10 minutes. On examination, he is unresponsive with a heart rate of 140/min, respiratory rate 60/min with retractions and head bobbing. He is peripherally cyanosed, saturating 80 percent in air and saturations slowly increasing to 88 percent in 100 percent Oxygen. Auscultation reveals bilateral extensive crepitations. The chest X-ray is suggestive of ARDS with bilateral diffuse infiltrates in lungs.

He was intubated and ventilated on PRVC mode. His initial settings were:

1. Tidal volume—90 ml (6 ml/kg)
2. FiO_2—100 percent
3. Rate—25
4. I:E ratio—1:2
5. PEEP—6

His saturations improved to 85 percent on the above settings and an ABG done showed pH (7.30), PCO_2 (45), PO_2 (47), HCO_3 (20.4), BE (–5) and saturation of 85 percent. To improve his oxygenation, his PEEP was increased to 8 and I:E ratio to 1:1. Following the intervention, his saturations improved to 95 percent. PEEP levels upto 15-18 cm H_2O may be required increasing the risk of barotrauma, cardiovascular compromise and hypotension.

Airleak Syndrome

Pneumothorax, Bronchopleural Fistula

Ventilation for airleak syndrome is challenging. Chest tubes are frequently required.

Ventilation Strategies

Using low mean airway pressures, low peak inspiratory pressures, low PEEP, lower tidal volumes, and lower inspiratory times are needed.

Other Modes useful in Airleak Syndrome are:

- High Frequency Oscillatory Ventilator (HFOV) delivers small tidal volumes at high frequency with lower peak and mean airway pressures.
- Patient has to be muscle relaxed.
- Patient cannot be suctioned frequently as disconnecting the patient from the oscillator can result in volume loss in the lung.
- Likewise, patient cannot be turned frequently and so, decubitus ulcers can occur.
- Patient should be turned and suctioned 1-2 times / day, if he / she can tolerate it.

Postoperative Ventilation following Open Heart Surgery

General Principles

One needs to understand the cardiac physiology associated with the lesion and corrective surgery as well as cardiopulmonary interactions in the post-operative period.

Hypoxia and hypercarbia should be avoided to prevent pulmonary hypertension that increases right ventricular afterload / chances of Right ventricular failure.

Excessive systemic vasoconstriction should be avoided to prevent increase in LV afterload.

Volume/pressure limited ventilation: Mode of ventilation has not shown to make any real difference in outcomes.

Excessive PEEP and excessive mean airway pressures should be avoided to prevent tamponade / low cardiac output.

Pulmonary and systemic vascular resistance can increase with pain, causing increased afterload on the heart.

Consider nitric oxide in patients with severe preoperative pulmonary hypertension, in postoperative period.

Chronic lung disease/Neuromuscular weakness: Tracheostomy is usually performed.

One needs to assess need for day / night / home ventilation.

Generally, low ventilator settings are needed. LP60 (USA) pressure controlled ventilator can be used.

Non-invasive positive pressure ventilation can also be tried to deliver PS and CPAP via tight fitting mask (BiPAP: Bi-level positive airway pressure). One can set a “back-up” rate in case of apnea (see Chapter 14).

CASE SCENARIO 3

A 13 year old immunized female child weighing 30 kg was admitted with complaints of sudden onset of weakness of lower limbs with inability to stand and bear weight for 2 days. The next day she developed weakness of both upper limbs such that she could only move her arms in the bed. She started to have decreased volume of voice and complained of some tingling sensation in both legs. There was no history of fever, cough, loose

stools, trauma, alteration in sensorium or seizures. She had an episode of fever with cough 2 weeks back which lasted for 3-4 days. On examination, she was alert, conscious and oriented. Her heart rate was 110/min and respiratory rate 30/min. She had shallow respiratory efforts with paradoxical respiration. CNS examination revealed quadriparesis with power in both lower limbs and upper limbs being 1/5 and 2/5 respectively. She had global areflexia. There was no objective sensory loss and no other focal deficits. She was diagnosed to have Gullian-Barre syndrome with respiratory muscle weakness supported by NCV findings. She was ventilated for neurogenic cause of respiratory failure on PRVC mode of ventilation with the following settings:

Tidal volume—200 (6-7 ml/ kg)
Rate—15
FiO_2—40%
Peep—3
I:E ratio—1: 2
Her ABG on the above settings was within normal limits.

Raised ICP (Intracranial Pressure)

Following points should be kept in mind:

1. Avoid ketamine, succinyl choline as these agents raise ICP.
2. Midline head up position is ideal.
3. Adequate sedation and muscle relaxation is required to prevent coughing and bucking on the ventilator (leads to raised ICP) and adequate analgesia during painful procedures.
4. Low PEEP (avoidance of excessive PEEP) to prevent ICP from going up.
5. Goal of ventilation is to keep normal PaO_2 and $PaCO_2$ to 30-35 mm Hg; hyperventilation is no longer recommended.[17] During impending herniation, $PaCO_2$ between 28-30 mm Hg may be required as an emergency measure.

Neonatal Ventilation[18]

Continuous positive airway pressure (CPAP)[19]: A continuous flow of heated humidified gas is circulated past the infants airway at a set pressure of 3-8 cm of H_2O maintaining an elevated end expiratory lung volume while the infant breathes spontaneously. CPAP is usually delievered by means of nasal prongs or nasopharyngeal tube. It improves oxygenation by an increase in the functional residual capacity. However, over-reliance on CPAP may be dangerous and it should only be used if infants show adequate respiratory effort, appear to be tolerating the procedure well and maintain adequate arterial blood (PCO_2 < 50 mm Hg, pH > 7.25, PaO_2 > 50).

With all CPAP devices, some air may get into the gut and cause gastric distention. This can be prevented by using an open ended orogastric tube-in-situ. CPAP effectively splints the chest wall, keeps the airways patent, thereby preventing obstructive apneas and atelectasis. Various studies have

documented the efficacy of CPAP in respiratory distress (Hyaline membrane disease) of mild to moderate degree.[19] Recently, trials have been conducted on using nasal intermittent positive pressure (NIPPV) and it has been found to have similar results as CPAP.

Conventional Neonatal Ventilation[20,21]

Pressure Limited Time Cycled Ventilation

The commonest type of ventilation used for neonates is pressure limited, time cycled ventilation where a peak inspiratory pressure is set and gas is delivered to achieve that target pressure. After the target is reached, the remainder of the gas volume is released into the atmosphere, as a result the tidal volume delivery with each breath is variable despite the recorded peak pressure being constant. Inspiration also ends after a preset time period.

In contrast, in volume limited modes, a preset volume is delivered with each breath, regardless of the pressure that is needed. Some ventilators also use airway flow as the basis of cycling in which inspiration ends when flow has reached a critical low or preset level (flow-cycled ventilation).

In pressure limited, time cycled continuous flow ventilators following parameters are set at the outset:

- Peak inspiratory pressure (PIP)
- Peak end expiratory pressure (PEEP)
- Inspiratory time (ti)
- Rate

This system is relatively simple and maintains good control over respiratory pressures.

Disadvantages

– Poorly controlled tidal volume.
– Does not respond to changes in respiratory compliance.
– Spontaneously breathing infants may receive inadequate ventilation and are at an increased risk for air leaks.

CASE SCENARIO 4

A neonate is born to a 24-year-old primigravida with pregnancy induced hypertension(PIH) through lower segment cessarian section due to uncontrolled hypertension at 34 weeks of gestation. He had a birth weight of 1.8 kg. He was tachypneic at birth with a rate of 68 / min and subcostal, intercostal and sternal retractions. He had grunting and had pulse oximeter saturations at 85 percent in room air which picked to 94 percent in oxygen. The chest X-ray revealed bilateral homogenous opacities suggestive of hyaline membrane disease (HMD). He was intubated and ventilated on pressure limited time cycled mode of ventilation with the following settings:

PIP—22
PEEP—4

FiO_2—100%
Rate—50
Inspiratory time—0.4 sec

His ABG on the above settings showed a pH of 7.25, PCO_2 (60), PO_2 (68), HCO_3 (18), BE (–5.0) and sats (95%). His ventilatory settings were revised to a PIP of 24 and rate was increased to 55. Following this, his PCO_2 came down to 44 and pH normalized.

Alternative Modes of Neonatal Ventilation

Due to disadvantages associated with conventional ventilation, following alternative strategies are being used increasingly:

Patient triggered ventilation (PTV): This is a form of ventilation where machine delivered breath is initiated in response to a signal derived from the patient's own inspiratory effort, thus synchronizing the onset of both spontaneous and mechanical breaths. The types of signals used to provide PTV to newborn vary and could be impedence, pressure or flow. The basic feature is shifting of control of breathing from clinician to patient and the newer generation of ventilators allow its application to the smallest of babies. PTV can be of the following types:

a. **Assist/control ventilation:** This is the best mode of ventilation in acute phase of illness as it requires least amount of patient effort and produces improved oxygenation at the same or lower mean airway pressure than conventional modes. In this type of ventilation, a positive pressure breath is delivered in response to patient's inspiratory effort (assist) provided it exceeds a preset threshold criteria. There is a back-up rate (control) in case, patient stops breathing. The inspiratory flow is proportional to patient effort and ventilation is tolerated well.
b. **Synchronous intermittent mandatory ventilation (SIMV):** In this mode of ventilation, mechanically delivered breaths are cycled at a rate set by the clinician but are synchronized to the onset of the patient's own breath.Patient breathes freely in between the mechanical breaths. This ensures less risk of 'fighting' or air leaks and sedation is not required. SIMV is particularly helpful for weaning from ventilation.[21]
c. **Pressure support ventilation (PSV):** This is similar to assist/control ventilation except that it is flow cycled, thus patient has full control over how much to breathe and for how long(ti). Although PSV can be used for full ventilation (PSV max), in practice it is genarally used as a weaning mode.
d. **Proportional assist ventilation (PAV).**
e. **Mandatory minute ventilation (MMV):** These are other promosing ventilatory strategies currently under development for clinical use but no data is available relating to its use in neonates.

Rescue Strategies for Management of Neonatal Ventilatory Failure

Despite improved ventilatory techniques, conventional ventilation may fail in certain situations. A commonly used parameter to assess the efficacy of ventilation is **oxygenation index** (OI).

$$OI = \frac{P_{AW} \times FiO_2 \times 100}{PaO_2}$$

P_{AW} = Mean airway pressure
FiO_2 = Concentration of inspired oxygen
PaO_2 = Partial pressure of oxygen
OI of 25-40 indicates insufficient ventilation with existing mode of support.
OI of > 40 indicates respiratory failure.
Various rescue therapies as given below are currently practiced:

A. *High Frequency Ventilation:* This can be of two types:
1. High Frequency Oscillatory Ventilation (HFOV).
2. High Frequency Jet Ventilation (HFJV).

In newborns, high frequency oscillation has been found to be effective in certain situations. During this type of ventilation, a continuous flow of fresh gas rushes past the source that generates the oscillation and a controlled leak or low pass filter allows the gas to exit the system. Both inspiration and expiration are active processes. Oscillations are generated at a frequency ranging from 3 Hz-15 Hz (1 Hertz (Hz) = 60 breaths) per minute. Pressure oscillations within the airway produce tiny tidal volume fluctuations around a constant distending pressure. The amplitude of the pressure, which varies from 15-50 cm H_2O, determines the tidal volume. This ventilation causes uniform recruitment of alveoli and there is significantly lower risk of air leaks. Earlier studies on HFOV had raised some doubts about the risk of IVH, however randomized controlled trials carried out with proper selection criteria have depicted a significantly better outcome with HFOV in certain conditions.[22] This mode of ventilation has been found to be effective in respiratory distress complicated by PPHN.[23] Only Sensorimedics 3100/3100A, a high frequency oscillator has been approved by FDA for early intervention (prophylactic HFOV) but it is not commonly preferred form of therapy.

CASE SCENARIO 5

A 29 year old 2nd gravida mother delivered at 38 weeks of gestation by lower segment cessarian section in view of Meconium stained liquor (MSL). At birth the baby was crying vigorously. He developed respiratory distress soon after birth. He was breathing at a rate of 80/min with severe retractions and was saturating 88 percent in 100 percent oxygen. His chest X-ray was suggestive of meconium aspiration syndrome (MAS). He was ventilated due to persistent hypoxia on the following settings:

Mode : Pressure limited time cycled

PIP	26
PEEP	3
Rate	60
FiO_2	100%
I:E ratio	1:3

His post ventilation ABG was : pH (7.182), PCO_2 (56), PO_2 (40), HCO_3 (16.2), BE (–7.5) and oxyhemoglobin saturation at 86 percent. An echocardiogram was done on suspicion of persistent pulmonary hypertension (PPHN) which showed pulmonary pressures of 90 mm Hg with systemic pressure being 82/40. He was started on dopamine to increase the systemic pressure and Milrinone for pulmonary vasodilation. Sodium bicarbonate was given to correct acidosis and PIP was increased to 28. I:E ratio was not increased due to a high risk of air leaks in MAS. After these interventions, the ABG improved to pH: 7.24, PCO_2: 45, HCO_3: 19.6, BE: – 2.6 but PO_2 remained low on 45 mm Hg. He was given a trial of high frequency ventilation on which his hypoxia slowly improved.

High Frequency Jet Ventilation is a variant of HFOV
and the differences are tabulated below (see Chapter 17)

	HFJV	HFOV
Rate(Hz)	1.5-3.00	3.00-15
Expiration	PASSIVE	ACTIVE
Special ETT (reintubation)	YES	NO
Gas Exchange	++	++
$PaCO_2$ reduction	++	++
PaO_2 increase	+-	+
Cardiac output	+-	–
Tracheal injury	++	?

Inhaled Nitric Oxide (INO) (see Chapter 18)

Nitric oxide (NO) appears to be ubiquitously distributed within universe. Critical care physicians have been most interested in the profound regulatory effects of NO on vascular tone. Inhaled nitric oxide distributes only to aerated lung where it rapidly diffuses from endothelial cells into subjacent vascular smooth muscle cells and stimulates Guanylate Cyclase to increase the concentration of Cyclic Guanosine Monophosphate that in turn causes smooth muscle relaxation. This localized vasodilator effect improves V/Q mismatch. NO that diffuses into vascular space is quickly converted to methemoglobin, thereby avoiding systemic vasodilator effect. Inhaled nitric oxide is particularly useful for treating persistent pulmonary hypertension complicating RDS. This can be used with both conventional and high frequency ventilation. Kinsella et al have reported outcome in nine cases of PPHN treated with INO. Within 15 minutes of initiation, PaO_2 increased from 55 mm Hg to 136 mm Hg and OI reduced from 60 to 26.[24] The first three had to be shifted to ECMO but the remaining six recovered completely.

Patients with pulmonary hypertension secondary to congenital heart disease may also benefit both diagnostically and therapeutically from NO. Sometimes, NO may combine with O_2 to form NO_2 and peroxynitrite, which could be highly toxic to the body. Thus, further studies are required to confirm the short term and long term safety of INO usage in very young

infants. The dose range used (10-80 parts per million) also needs to be standardized.

Summary

1. Remember that shock and post resuscitation are important indications for ventilation, in addition to respiratory failure and neuromuscular disease.
2. Clinical monitoring of adequate chest rise and oxygen saturations is very important (regardless of volume, pressure or time cycled mode).
3. If ventilator fails, or when in doubt, remove endotracheal tube and try bag mask ventilation.
4. Think about pneumothorax in a patient on mechanical ventilation.
5. Pulse oximetry and ABG facility is necessary for ventilation.
6. Hypoxia should be ruled out/corrected before sedating an agitated child.
7. Do not muscle relax/sedate patient with upper airway obstruction unless very confident in endotracheal intubation.
8. Low tidal volume is permitted to prevent lung trauma (permissive hypercapnia).
9. Endtidal CO_2 monitoring and pulmonary graphics monitoring is desirable if available.

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5 Chapter

Advanced Mechanical Ventilation: Newer Modes

Praveen Khilnani

Ventilatory strategies in the past evolved from surgical and anesthetic practice. In the immediate postoperative period, tidal volumes of 10 and 15 ml/kg ("sigh volumes") were used to prevent the microatelectasis that accompanied shallow or inadequate ventilation. In addition, blood gases were "normalized". It has become more apparent that this may place the injured lung at risk of further damage. Therefore, even more important than the technique or the machine, is the need to develop a strategy of treatment based on the pathophysiology.

Use of newer modes and different modalities of ventilation is rapidly evolving using a combination of following strategies:

- Using decreased tidal volumes (Vt) 7 ml/kg.
- Decreasing peak inspiratory pressure (PIP).
- Increasing inspiratory time (T insp).
- Using increased mean airway pressure.
- Washing out or bypassing dead space.
- Permissive Hypercarbia and Hypoxemia.

In addition, other techniques may be used to meet other specific goals of:

- Treatment of asymmetric lung disease.
- Decrease work of breathing.
- Guaranteed tidal volume at lowest PIP.
- Lung rest.

INVERSE RATIO VENTILATION (IRV)

- *Strategy:* Decrease PIP, increase (T insp), increase mean airway pressure.
- Inverse ratio ventilation is a technique first popularized by Reynolds in England, who applied this method to newborn with hyaline membrane disease. He reported better oxygenation and less barotrauma. This method became the forerunner of pressure-limited ventilation. Basically, it is controlled by positive-pressure ventilation with an inspiratory time ratio >1:1 or a duty cycle of > 0.5. Duty cycle (Ti/Ttot) is the ratio of the inspiratory time (Ti) to the total breath cycle duration (Ttot).

Inverse ratio ventilation can be established by any of the following methods:

a. Timed-cycled, volume-cycled, or pressure controlled ventilation with the inspiratory time (Ti) adjusted to the desired level.
b. Pressure-limited ventilation (either timed or volume-cycled ventilators) with a prolonged inspiratory time, or
c. Volume cycling with a prolonged inspiratory hold.

Improved ventilation reported with this technique probably results from increased duration of the inspiratory phase. This allows areas with longer time constants to receive greater flow than would otherwise occur with conventional volume-controlled ventilation with the usual I:E ratio. Improvement in gas exchange during inverse ratio ventilation is attributed to more effective alveolar recruitment and better distribution of ventilation during the extended inspiratory phase, thus decreasing deadspace ventilation.

The short expiratory time invariably induces intrinsic PEEP. Peak airway pressure (is lower than that with continuous positive-pressure) and increased functional residual capacity are responsible for the improvement in oxygenation.

Inverse ratio ventilation imposes a nonphysiologic breathing pattern and requires sedation or paralysis. There is often little effect on cardiac output at I:E ratio of < 4:1 in the volume repleted individual, but the occurrence of pneumothoraces may be as high as 25 percent. This may correlate more with length of time on inverse ratio ventilation than the I:E ratio or the mean airway pressure.

Inverse ratio ventilation is often used in patients with respiratory distress syndrome with refractory hypoxemia (PaO_2 < 60 mm with an FiO_2, > 80%) despite the use of PEEP > 15 cm H_2O with CPPV. There are no controlled studies to show that inverse ratio ventilation reduces morbidity and mortality rates. In fact, the beneficial effect is inconsistent and the exact role played by changing the I:E ratio, as opposed to alterations in mean airway pressure or the incorporation of a decelerating inspiratory flow, is difficult to ascertain. It is possible that it is the absolute duration of inspiration that is the most significant feature in the apparent success of inversed I:E ratio ventilation. Recently, East et al, reported on their success with the use of a computerized protocol for pressure control inverse ratio ventilation in patients with acute respiratory distress syndrome (ARDS). Their goal was to provide the highest mean airway pressure at the lowest PIP. They used FiO_2, and intrinsic PEEP values to determine oxygenation. The computerized protocol followed a specific algorithm for ventilator manipulations based on very appropriate physiologic strategies. They attained their goals with no apparent increase in barotrauma. Perhaps more importantly, it proved the feasibility of this protocol to allow for a more systematic approach.

AIRWAY PRESSURE RELEASE VENTILATION (APRV) (FIG. 5.1)

Strategy: Decreased PIP increased (T insp) mean airway pressure.

Airway pressure release ventilation is a form of continuous positive airway pressure (CPAP) that releases the airway pressure from one preset CPAP level to a lower CPAP level. This allows a spontaneously breathing

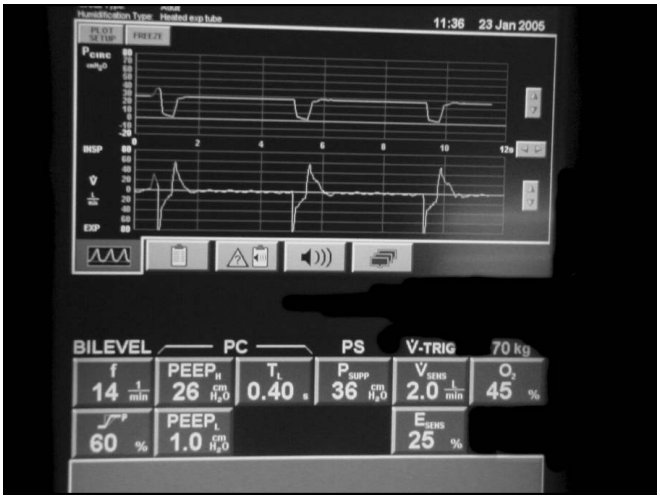

Fig. 5.1: APRV *(For color version see Plate 1)*

patient to exhale to a lower lung volume. The unique feature of airway pressure release ventilation is the augmentation of alveolar ventilation by a decrease in airway pressure and lung volume.

Preset variables are the initial CPAP level, the frequency of airway pressure releases (similar in concept, to intermittent ventilation (IMV), the level to which CPAP reduces during release, duration of the airway pressure release. The duration of the expiratory release (expiratory time) is usually < 1.5 sec. Peak airway pressure during airway release ventilation is 30 to 75 percent that during CPPV and may explain the finding that it has less of an effect hemodynamics than does CPPV. Peak airway pressure never, exceeds the CPAP level. Since, airway pressure during airway release ventilation never exceeds the CPAP level, it may be that inverse ratio ventilation which reduces morbidity, clinically feasible to commence airway pressure release ventilation in a patient receiving mask CPAP therapy without the need for tracheal intubation.

Weaning occurs by lowering the frequency airway pressure release, until the patient is breathing with CPAP alone. From a synchronization standpoint, augmentation of ventilation during airway pressure release ventilation is similar to conventional IMV. Airway pressure release ventilation has not been shown to significantly improve oxygenation in studies of humans with acute lung injury. It appears more effective in improving alveolar ventilation than oxygenation. It results in a lower $PaCO_2$ value than conventional ventilation at a similar minute ventilation.

The rationale for the development of airway pressure release ventilation is similar to inverse ratio ventilation, i.e. to open, maintain and stabilize the collapsed alveoli without peak airway pressure and the hazard of barotrauma. Thus, the initial CPAP level (or insulation pressure in inverse ratio ventilation) is responsible for stabilization of lung units and the expiratory phase is responsible for ventilation. Although the pressure

tracings of inverse ratio ventilation with pressure limit closely mimic airway pressure release ventilation, the former usually has higher peak and mean airway pressures and doesn't allow for spontaneous breathing. In contrast to inverse ratio ventilation, airway pressure release ventilation allows the patient to breathe spontaneously between ventilator breaths, without requiring sedation and paralysis. In addition, the increase in functional residual capacity (FRC) in inverse ratio ventilation depends more on intrinsic PEEP because of higher closing volumes in children and CPAP levels that are often below critical opening pressure of airways, it is doubtful that airway pressure release ventilation will be useful for prolonged ventilation in children with acute lung disease. However, further studies are being performed and more data is accumulating on its use in patients with acute respiratory failure.

PRESSURE SUPPORT VENTILATION (PSV)

Strategy: Decreased work of breathing.

This is a patient-triggered, pressure-limited mode of positive pressure ventilation that delivers a preset positive pressure during the inspiratory phase (Fig. 5.2). Commonly, a pressure plateau is maintained until the patient's inspiratory flow decreases to a specified level at which time exhalation occurs. Unlike pressure limited ventilation, during pressure support the patient determines the initiation of inspiration, inspiratory times, flows and tidal volume, and the termination of inspiratory phase. The patient's effort, the preset pressure limit, and the respiratory system impedance determines tidal volume (Vt). Inspiratory time and Vt can vary on a breath-to-breath basis.

Pressure support ventilation is reported to have many benefits. Most agree that it does compensate for the increased work of breathing due to the endotracheal tube and the ventilator demand valve. Improved synchrony between the patient and machine may help to explain the increased sense of comfort that pressure support ventilation provides. The most important physiologic aspect of pressure support ventilation may be its ability to better match the patient's inspiratory flow demands, thereby

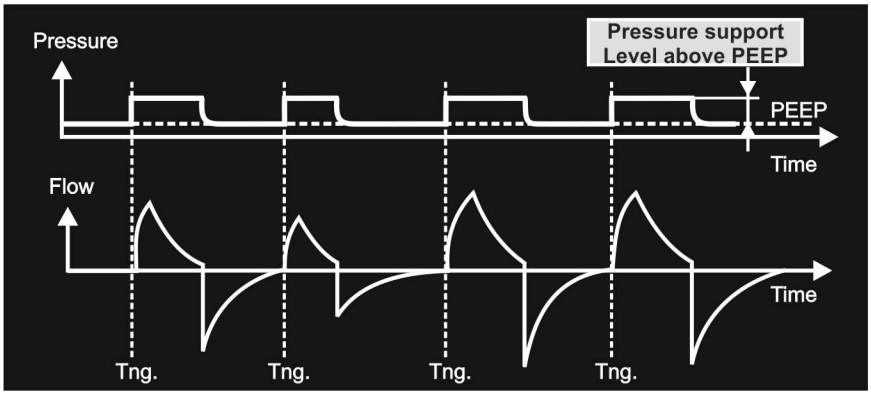

Fig. 5.2: Pressure support/CPAP: Pressure flowtrace

minimizing respiratory muscle effort as compared with other forms of mechanical ventilation. Pressure support ventilation should allow patients with mechanical impairment to ventilation to acquire larger inspiratory tidal volumes at the same level of effort or the same level of Vt at a lower level of inspiratory work.

Other benefits of pressure support ventilation include the reduction in the activity of the inspiratory muscles during spontaneous breathing. Values of 20 cm H_2O of pressure support ventilation abolish the pattern of electromyographic activity indicative of muscle fatigue. It may decrease oxygen consumption by the respiratory muscles and improve respiratory muscle loading while decreasing the respiratory muscle work per liter of ventilation as well as total muscular work per minute. Decreased intrinsic PEEP, elastic work of breathing, and oxygen cost of breathing have also been reported. Although not documented, some feel that it improves endurance conditioning of the respiratory muscles.

Proponents suggest initial ventilation at maximum pressure support ventilation. This is the level of pressure support required to produce a Vt of 10 to 12 ml/kg, and corresponds to the level where inspiratory work is least. Gradually, the pressure support ventilation level is decreased to < 10 cm H_2O (above PEEP), when extubation can be performed.

Since each breath must be initiated by the patient, pressure support ventilation should be used with caution in patients with an unstable respiratory drive or highly changeable respiratory impedance (e.g. a patient with reactive airway disease). In the latter case, as with all forms of pressure-limited ventilation, as the patient's impedance changes, delivered VT may be affected. Synchronized mandatory ventilation (SIMV) and pressure support ventilation may be preferable when one requires complete mechanical support.

PRESSURE-REGULATED VOLUME CONTROL (PRVC)

Strategy: Guaranteed Vt at lowest PIP and decreased work of breathing.

This is the new mode of controlled ventilation found on the Servo 300 ventilator (Fig. 5.3). It uses a decelerating flow generator (as used in the Pressure Control mode on the 900 C ventilator) as a pressure generator (pressure remains constant). The ventilator evaluates the exhaled volume on a breath-by-breath basis and will reset the pressure support level as needed to guarantee the Vt. The flow pattern often decreases the PIP (by approximately 5 to 7 cm H_2O) when compared with the same volume delivered in a volume control (constant flow) mode. Mean airway pressures may increase, averaging about 1 cm H_2O. Therefore, it overcomes the limitation of pressure support ventilation and mandatory minute ventilation by assuring a constant Vt, even with a lung with changing pulmonary mechanics.

PROPORTIONAL ASSIST VENTILATION (PAV)

Strategy: Decrease PIP and decrease work of breathing, increase volume of spontaneous breaths.

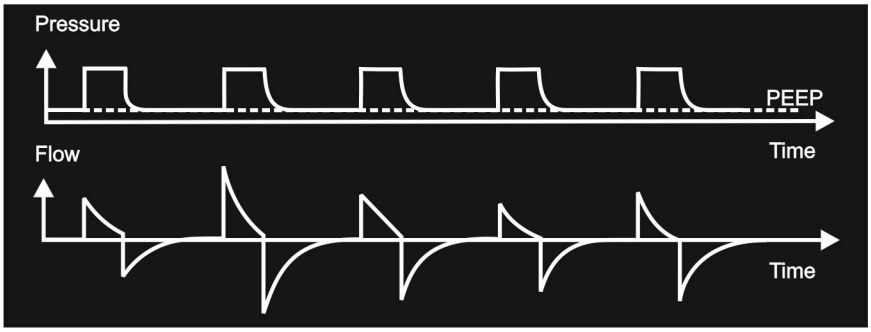

Fig. 5.3: Pressure regulated volume control: pressure flowtrace

First described by Younes as a method to alter the mechanical load of the respiratory system, this method of positive pressure ventilation holds great promise for those patients with adequate respiratory drive. Essentially, the ventilator changes pressure at the airway in proportion to the inspired volume (elastic assist), the inspired flow (resistive assist), or both inspired volume and flow. The delivered volume or pressure varies according to the feedback signal the ventilator receives proportionate to the patient's elastic and/or resistive load. Thus, the ventilator simply reduces the total respiratory load and leaves the patient in total control of the breathing pattern. Conceptually, it is similar to the use of helium to decrease the respiratory load, or an intra-aortic balloon pump to decrease the load on the left ventricle. It also approximates what an individual may do while "hand bagging" a spontaneously breathing patient. As the patient takes a greater inspiration, the person bagging will squeeze the bag harder, i.e. the volume delivered will be proportional to the patient's inspiratory effort.

NONCONVENTIONAL TECHNIQUES

These techniques represent a new approach to the management of patients with respiratory failure. Most of the techniques make use of very small Ventilators (Vts) or no Vts. Many studies suggest that these techniques can maintain adequate gas exchange under experimental conditions in which traditional concepts of gas transport no longer hold. Except for high-frequency ventilation, all the other modes attempt to decrease the respiratory frequency.

High Frequency Ventilation

High frequency ventilators may be classified by their exhalation phase. In one group of ventilators (such as the jet ventilator), exhalation is passive. In the other group, e.g. oscillators, the ventilator actively helps exhalation. Although there are many theories on how high frequency ventilation works, simple convection remains important despite the use of volumes often well below the deadspace volume (please refer to chapter on High Frequency Ventilation).

Apneic Oxygenation

The application of apneic oxygenation involved ventilating an animal with 100 percent oxygen for 30 to 60 minutes to remove nitrogen from the lung. Then a source of oxygen was placed at the airway while the animal remained apneic. During the apneic period, $PaCO_2$ increased at a rate of 3 to 6 mm / min, the PaO_2 decreased from approximately 500 mm at about the same rate. Apneic oxygenation appears to have little clinical value in patients with acute lung disease, except as an adjunct with extracorporeal methods.

Tracheal Insufflation of Oxygen

This is a technique in which a constant flow of gas is insufflated into the trachea via a catheter placed near the carina. In apneic animals, oxygenation remained adequate but respiratory acidosis followed. In an animal model, tracheal insufflation of oxygen decreased both the $PaCO_2$ values and spontaneous minute ventilation. This technique appears to have limited clinical utility except, as with apneic oxygenation, as an adjunct with extracorporeal methods. It also may be helpful as a potential emergency procedure in patients with an airway that is difficult to intubate.

Constant Flow Ventilation

This is a method in which a constant flow of gas at a relatively high flow rate of about 1.5 to 3 L / min / kg is insufflated through two catheters placed at the carina. During constant flow ventilation, the lung remains motionless, with sufficient airway pressure to maintain patency of airway and alveoli. Turbulence, molecular diffusion, cardiogenic and, most importantly, collateral ventilation seem to be important as the primary methods of gas transport with constant flow ventilation. Because of poor collateral circulation in humans, constant flow ventilation is largely ineffective for total alveolar ventilation. It is primarily a tool to study physiologic phenomena that are affected by breathing. However, Gilbert et al reported on the use of a modification of constant flow ventilation for a patient with a bronchopleural fistula (BPF). He used constant flow ventilation in tandem with a conventional ventilator but only during the exhalation phase (intermittent flow expiratory ventilation). This allowed them to decrease the Vt on the conventional ventilator by one-third, thus decreasing the PIP significantly.

Liquid Ventilation (LV)

Ventilation with an oxygenated liquid perfluorochemical has been used experimentally in premature animals with respiratory failure. It has a high solubility for oxygen and CO_2 and a low surface tension. It has been shown to eliminate the interfacial surface tension to improve distribution of pulmonary blood flow and support physiologic gas exchange without deleterious consequences when conventional techniques have failed.

More recently, Greenspan et al tried this method in three human preterm neonates. Oxygenated perfluorochemical was allowed to flow into

the patient's lungs by gravity for two 3 to 5 minute cycles. Each cycle consisted of Vts of 15 ml/kg of perfluorochemical delivered over 5 seconds. Each Vt was held within the infant's lungs for 10 seconds and then allowed to drain by gravity. This was repeated at a rate of two to three liquid breaths per minute. After liquid ventilation, conventional ventilation and neonatal management resumed. Results showed that after a brief trial of liquid ventilation, two of the three neonates showed improved oxygenation and all three showed improvement in total respiratory compliance after return to gaseous breathing.

This physiology for perfluorochemical breathing has been previously described. After equilibration to 1 atm of pure oxygen, a perfluorocarbon may carry 45 to 55 ml dissolved oxygen per 100 ml solvent. During liquid breathing, the gel lining of the alveolus makes direct contact with the solvent, which is "inhaled and exhaled" in Vts (15 ml/kg). This eliminates air fluid interfaces and, thus, the resultant surface tension is eliminated. The compliance of the lung is dramatically enhanced, thereby eliminating the factors that cause maldistribution of ventilation in the surfactant-deficient lung. More recently, a perfluorocarbon was instilled in the lung at 30 ml/kg and used in tandem with mechanical ventilation. This was referred to as perfluorocarbon associated gas exchange. Documentation about the fact, that it has advantages over conventional ventilation, is lacking. Currently, liquid ventilation is not routinely used due to lack of good clinical evidence.

Altering lnspired Oxygen and Carbon Dioxide Concentration

A low alveolar oxygen tension increases pulmonary vascular resistance (hypoxic pulmonary vasoconstriction) and a high alveolar oxygen tension decreases pulmonary vascular resistance. With certain types of congenital heart disease such as hypoplastic left heart syndrome, it is critical to control pulmonary blood flow and prevent pulmonary flooding. One approach is to decrease the FiO_2 to less than 0.21 by blending room air with nitrogen. The exact FiO_2, delivered must be monitored to avoid administering, excessively low inspired oxygen. The other approach especially in mechanically ventilated patients, both preoperatively and postoperatively, is to increase the inspired carbon dioxide concentration ($FiCO_2$). Increased $FiCO_2$ also increases pulmonary vascular resistance. One of the difficulties with an increased $FiCO_2$ is increased spontaneous ventilatory drive as a result of an increased $PaCO_2$. This increases the work of breathing and with marginal cardiac reserve may impose undue strain on the heart. Therefore, increased $FiCO_2$ should be used judiciously, avoiding an increased workload on the heart in spontaneously breathing patients.

Helium-Oxygen Mixture (Heliox)

Helium-oxygen mixtures have much lower density than oxygen-nitrogen mixtures and reduce resistance to air flow. This has been utilized in the properly successful treatment of upper airway obstruction after extubation in children. Helium-oxygen mixture has been used in upper airway

obstruction due to laryngotracheobronchitis and postextubation subglottic edema in infants and children. Helium is usually administered in at least 30 to 40 percent oxygen through a tight fitting facemask. Use of an oxyhood is not recommended, since helium tends to separate, and layer at the top of the oxyhood with the patient breathing very little helium. Recently, helium-oxygen mixture has been shown to improve gas exchange in neonates with respiratory distress syndrome. Oxygenation should be monitored during administration of helium-oxygen mixture to avoid hypoxia, especially in neonates. In adults, helium-oxygen mixture has also been used in the management of severe lower airway obstruction in asthma. Since the ventilator transducers are calibrated with air-oxygen mixture, the true volumes delivered tend to be different from preset values. Therefore, when helium-oxygen mixture is administered through the ventilator, direct volume measurements are necessary to ensure that the appropriate Vt is being delivered. Heliox is not yet freely available in India.

NEURALLY ADJUSTED VENTILATORY ASSIST (NAVA) (FIG. 5.4)

Conventional ventilator technology uses a pressure drop or flow reversal to provide assistance to the patient. This is the last step of the signal chain leading to inhalation, and it is prone to disturbances such as intrinsic PEEP, hyperinflation and leakage. The earliest signal that can be registered with a low degree of invasivity is the excitation of the diaphragm. This signal is proportional to the integrated output of the respiratory center, and thus controls the depth and cycling of the breath. The excitation of the diaphragm is independent of pneumatic influence and insensitive to the above problems with pneumatic triggering technologies. By following diaphragm excitation and adjusting the support level in synchrony with the rise and fall of the electrical discharge, the ventilator and the diaphragm will work with the same signal input. In effect, this allows the ventilator to

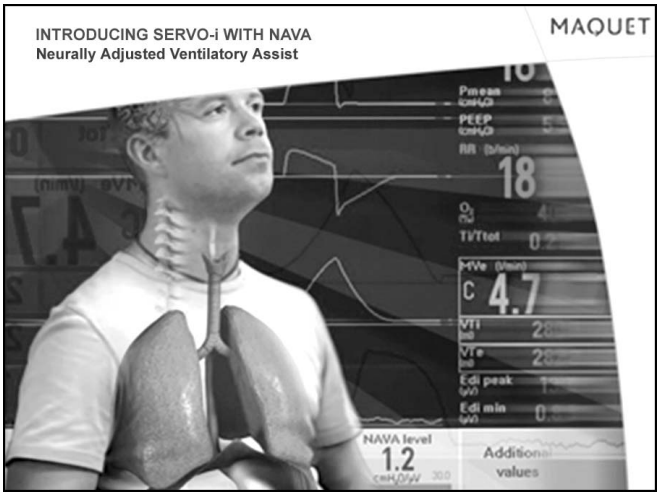

Fig. 5.4: Naturally adjusted ventilatory assist
(*For color version see Plate 1*)

function as an extra muscle, unloading extrarespiratory work induced by the disease process.

Asynchrony during SIMV-PS

The trigger delay from neural inspiration to the start of flow generation by the ventilator is typically about 100 ms with flow or pressure triggering. In a neonate with a total cycle time of 250-300 ms, this may constitute significant asynchrony while in an adult patient it may not be noticed. Continued insufflation during neural exhalation may pose a larger problem as this may aggravate hyperinflation, intrinsic PEEP and triggering delays.

NAVA

NAVA is independent of pneumatic disturbances and will provide respiratory assistance in full synchrony with the respiratory effort made by the patient (respiratory rate, duration of the breath and the tidal volume). The neural respiratory rate may be modified by the NAVA level. But synchrony will still be maintained.

The basic respiratory rhythm is generated by the respiratory center of the brain. The interval between bursts determines the respiratory rate and the intensity of the bursts determines the degree of activation of the respiratory muscles. The burst produced by the respiratory center travels along the the phrenic nerve and activates the diaphragm electrically. This excitation is captured by the electrode array of the Edi catheter and is transferred to the Servo-i, which delivers assistance to the patient in proportion to the signal obtained. Meanwhile the diaphragm signal induces the release of a neurotransmitter that directly activates the respiratory muscles. The subsequent shortening and descent of the diaphragm induce a drop in transpulmonary pressure below ambient, which is followed by inflow of air (Fig. 5.5).

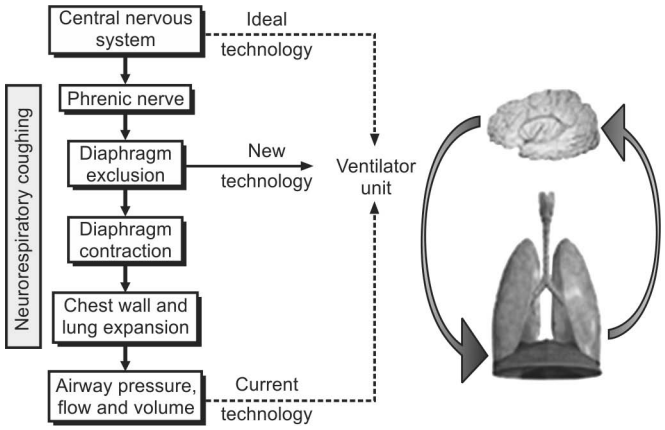

Fig. 5.5: Respiratory control

Method

Parts needed for NAVA:

- NAVA Software
- Edi Module
- Edi Module Cable
- Edi Catheter
- Servo-i ventilator with NAVA

The electrical discharge of the diaphragm is captured through the introduction of a standard nasogastric tube fitted with an electrode array. Before the introduction of the catheter, the length of the catheter to be introduced into the patient is estimated by measuring the distance from the xiphoid process and up over the ear and to the tip of the nose. Make a note of the distance and place the catheter with this mark at the nostrils. By carefully following this instruction, satisfactory signal quality will be obtained in 95% of the cases. The nasogastric tube should be immersed in water for 5 minutes, which makes the catheter surface slippery. This avoids the need for other lubricants and assists in effortless introduction of the catheter. Insert the catheter with the previously estimated depth measured from the nostrils. Catheter position can now be checked by injecting a small amount of air and listening for bubbles with a stethoscope. Plug in the NAVA module to the Servo-i and connect the Edi catheter to its outlet. The Edi catheter positioning window of the Servo-i will assist in verifying proper Edi catheter positioning, through inspection of the esophageal ECG. A prominent P-wave should be seen in the uppermost channel with a continued decline of P-wave amplitude in the lower leads (Fig. 5.6).

As the diaphragm depolarization is captured, the signal is transmitted to the Servo-i which will deliver inspiratory support in proportion to the electrical activity of the diaphragm. In effect this provides extra muscle power and increases the efficiency of the respiratory muscles.

Potential Benefits with NAVA

- Improves patient ventilator interaction: Synchrony by proportionally assisting each breath with minimum time delay.

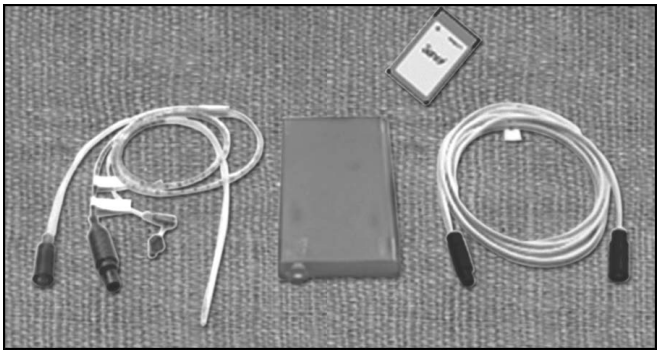

Fig. 5.6: Maquet (*For color version see Plate 1*)

- Enhances respiratory monitoring: Monitoring the electrical activity of the diaphragm (Edi). Information about the inspiratory drive and the brain signaling.
- Reduces work of breathing: Missed trigger efforts do not exist. Intrinsic PEEP does not affect triggering.

Timely delivery of assistance

- Provides improved and safer ventilation: The patient controls the tidal volume. No run-away phenomena. Back-up function with mechanical triggering, pressure support and pressure control.
- Reduces need for sedation / paralysis: As a result of improved adjustments by the ventilator to the inherent breathing pattern, sedation can probably be reduced.
- Adapts to altered metabolic demand (e.g. fever): The proportional assist built into NAVA will compensate for altered metabolic demands resulting in increased amplitude of Edi.
- Prevents disuse atrophy: As the diaphragm is kept continuously activated, diaphragm atrophy is ruled out.
- Shortens weaning time: Current experience shows that early extubation is possible with a higher degree of certainty as the decision to extubate is founded on knowledge both of the true respiratory drive and the degree of ventilator assistance and its effect on the electrical activity of the diaphragm.
- Improves non-invasive ventilation: As the pneumatic coupling is no longer critical for the trigger sensing, leakage is acceptable and will not result in autocycling.

Evidence for NAVA: Beck et al have published animal data, however larger clinical trials are lacking, therefore routine use of NAVA in adults or pediatrics cannot be recommended until more clinical data is available.

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6 Chapter

Patient Ventilator Dyssynchrony

Deepika Singhal, Praveen Khilnani

One of the most frequent reasons for instituting mechanical ventilation is to decrease a patient's work of breathing. For the most effective unloading of the inspiratory muscles, the ventilator should cycle in synchrony with the activity of a patient's own respiratory rhythm. The interplay between these two pumps is complex, and problems can arise at several points in the respiratory cycle: the onset of ventilator triggering, the rest of inspiration after triggering, the switch from inspiration to expiration, and the end of expiration. Newer ventilators with better and sensitive pressure and flow sensors and technologies such as NAVA (neurally adjusted ventilatory assist) are being employed to improve patient ventilator dyssynchrony. We shall discuss the physiological basis and current status of practical relevance of these technologies.

VENTILATOR-RELATED FACTORS THAT AFFECT PATIENT-VENTILATOR INTERACTION

Triggering

1. Ineffective trigger (Fig. 6.1A)
   - — Excessive intrinsic positive end-expiratory pressure.
   - — Delayed termination dyssynchrony.
   - — Maladjusted sensitivity level.
2. Auto-triggering
   - — Maladjusted sensitivity level.
   - — Excessive water in circuit.
   - — Air leaks in endotracheal tube cuff, ventilator circuit, chest tube.
   - — Cardiac oscillations.
3. Double triggering (Fig. 6.1B)
   - — Premature termination dyssynchrony.

Ventilator Causes of Patient Agitation

1. Ventilator disconnection.
2. System leak, circuit malfunction.
3. Inadequate fraction of inspired oxygen.
4. Inadequate ventilator support.

Cycling Off

- Inappropriately set cycling variable for patient.

Dead Space

- Increased dead space in circuit causes increased workload and work of breathing.

TRIGGER VARIABLE

The trigger variable is usually pressure or flow. With pressure triggering, in order to trigger the ventilator and initiate the inspiratory flow, the patient must decrease the pressure in the ventilator circuit to a preset value, which will then open a demand valve. With flow triggering, the patient triggers the ventilator when the respiratory muscles generate a certain preset inspiratory flow. It is generally believed that triggering of the ventilator is better with flow than with pressure. The clinical significance is unclear in terms of the work of breathing and patient ventilator interaction. Pressure sensors in current ventilators are much improved, reducing any difference between flow- and pressure triggering systems. Recent studies in patients with different diseases show that the difference in the work of breathing between flow and pressure triggering is of minimal clinical significance.

INEFFECTIVE TRIGGERING

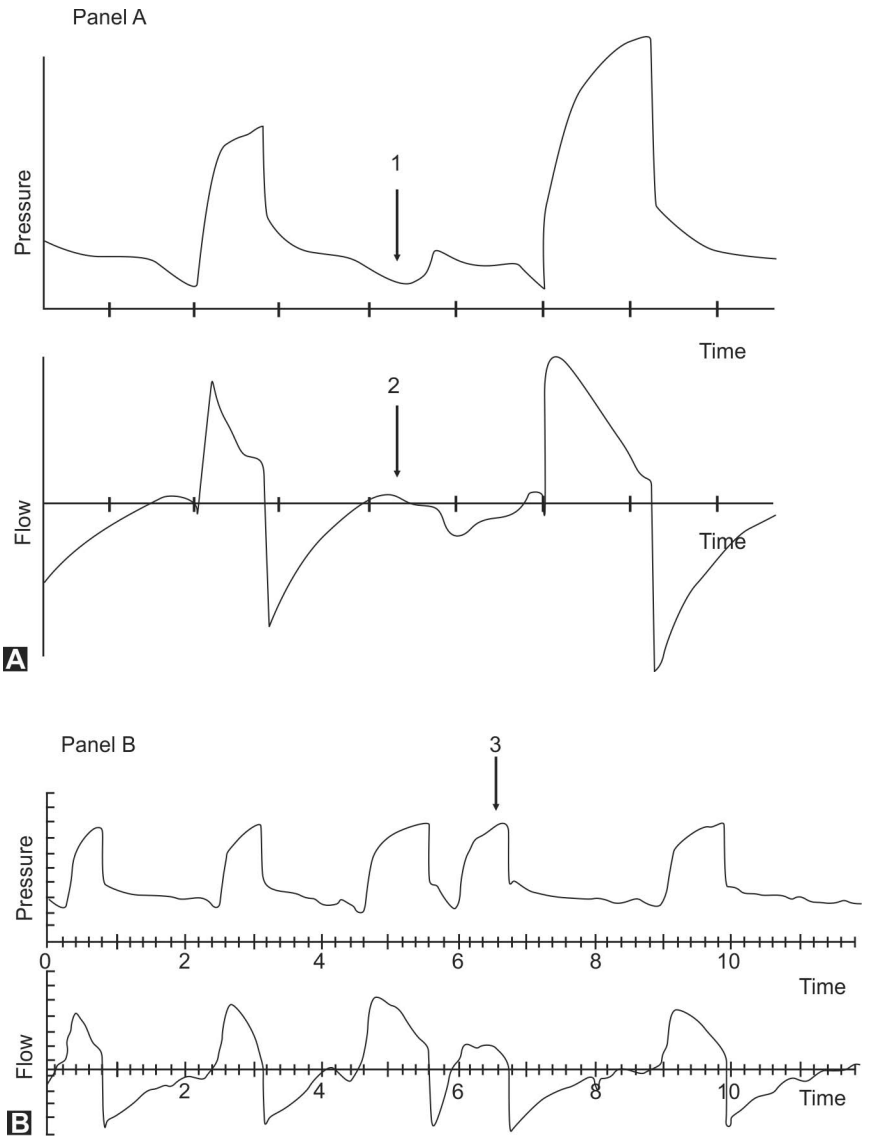
Apart from asynchrony between the patient and ventilator and wasted effort, ineffective triggering may have serious consequences for inspiratory muscle function. Ineffective triggering often occurs during exhalation of the previous mechanical breath, and the inspiratory muscles are activated to contract when they would normally be lengthening as lung volume decreases. This type of muscle contraction causes ultra structural damage to muscle fibers and reduced strength.

Autotriggering

Ideally, during assisted support the triggering of the ventilator should be the result of inspiratory muscle contraction. In some circumstances, however, a mechanical breath may be triggered without an inspiratory effort (autotriggering). It may be caused by random noise in the circuit, water in the circuit (which can cause abrupt changes in circuit resistance), leaks and cardiogenic oscillations. Autotriggering occurs more often with low respiratory drive and breathing frequency and when dynamic hyperinflation is absent. The risk of triggering increases with greater sensitivity of the triggering system. Imanaka and colleagues found that decreasing the flow threshold for triggering from 2 to 1 L / min increased the frequency of autotriggering from 15 to 22%. Autotriggering can interfere with patient management, reducing $PaCO_2$ and thus patient effort.

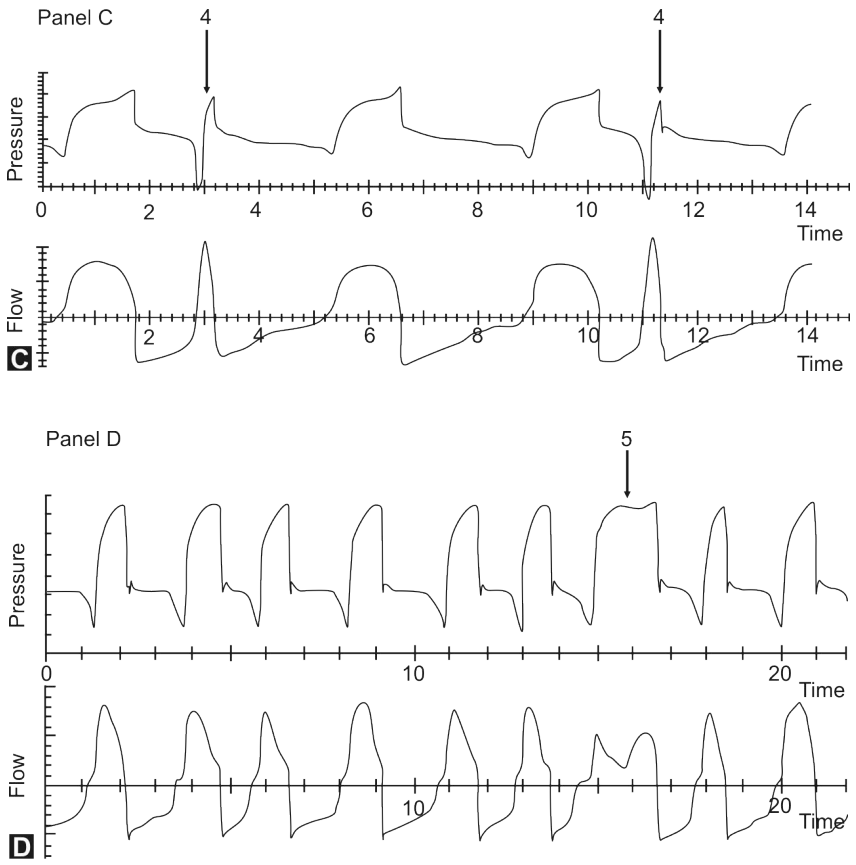
Breath Delivery Asynchrony

For optimal breath delivery synchrony, several parameters need to be met. The ventilator must deliver a sufficient amount of flow to consistently match or exceed the spontaneously breathing patient's inspiratory demand,



Figs 6.1A and B: Examples of asynchronies. Panel A demonstrates ineffective triggering which is marked by a decrease in airway pressure (arrow 1) and simultaneous increase in airflow (arrow 2). Panel B demonstrates an example of double triggering (arrow 3)

deliver an adequate Tidal Volume (V_T), and an adequate rise-to-pressure time should be set (in pressure breaths only). The use of ventilator graphics and proficient patient assessment skills are paramount to achieving this sometimes-difficult phase of the breath delivery synchronization. Patient sedation requirements should be minimal if breath delivery synchrony is optimal.



Figs 6.1C and D: Examples of asynchronies. Panel C shows an example of short cycling (arrow 4). Panel D shows an example of prolonged cycling (arrow 5)

Flow starvation is a common cause for breath delivery asynchrony in volume ventilation. If patients do not have enough inspiratory flow to meet their demands, they will pull against their own impedance as well as the ventilator's. This will increase the WOB substantially, sometimes greater than that of unassisted spontaneous breaths. It will not only be obvious on the ventilator graphics, but in most cases it will be clearly visible during the patient assessment. This is more of an issue in patients with a high respiratory drive or a high minute volume, as seen in a septic patient.

Several things can be done to correct flow starvation. In volume ventilation, the inspiratory flow can be increased. One concern with increasing the flow too much is that it shortens the T_I; the mechanical (ventilator's) T_I is shorter than the neural (patient's) T_I. Studies show that rapid inspiratory flows can increase the neural breathing frequency. It can also cause breathing discomfort due to excessively forceful gas delivery.

Another option for correcting flow starvation is to switch the patient from volume ventilation to pressure ventilation. Pressure controlled ventilation has several advantages, two of which are independent control of T_I and variable patient controlled inspiratory flow. Patients can receive the flow they demand independent of the set T_I. Patients with high respiratory drives and efforts need to have enough pressure to provide enough flow to meet their demand.

Another aspect of the inspiratory phase during pressure-controlled and pressure-supported breaths is the fast rise-to-pressure time that is required to reach the set pressure at the start of the breath. Some patients with high respiratory drives may be comfortable with the fast flow and pressure spike. Others may become asynchronous with the ventilator due to this "ringing" or "spiking", which is noticed on the pressure-time scalar. Most new microprocessor ventilators have a control that allows the RCP to tailor or shape the breath for patient comfort. This is done by the "rise time" or "slope" parameters, depending on the manufacturer of the ventilator.

Breath Cycling Asynchrony (Figs 6.1C and D)

Breath cycling is defined as the "cycling off" of the mechanical inhalation or switching from the inspiratory phase to the expiratory phase within the breath cycle.

There are two types of inspiratory times: neural T_I and mechanical T_I (T_I neural and T_I mech); they need to be in-sync with one another. Neural and ventilator mismatching could cause asynchrony in triggering, breath delivery and / or breath cycling.

Premature termination. If a mechanical breath is terminated before the patient desires (premature termination), the patient continues to contract inspiratory muscles, allowing pressure to overcome elastic recoil and resulting in the ability to meet the trigger threshold and initiate a new breath, called double triggering. Premature termination of ventilator flow causes excessive inspiratory muscle work into and during the expiratory phase and an overestimation of respiratory rate.

Delayed termination. On the other hand, if the mechanical breath does not terminate when the patient's muscular inspiration is complete (delayed termination), the time for exhalation is limited and expiratory workload and sometimes auto-PEEP increase, resulting in possible ineffective and / or failed trigger on the following breath. Delayed termination causes patients to resist or "fight" incoming ventilator flow by using their expiratory muscles. This resistance results in increased expiratory load and excessive PEEPi, thereby leading to possible pneumothoraces, barotrauma, and altered cerebral blood flow.

Improving patient ventilator synchrony. Employing the optimum trigger mechanism setting on the ventilator and clinical monitoring of the patient is the key to success to prevent patient ventilator dyssynchrony as discussed earlier. Newer technologies such as NAVA: [neurally adjusted ventilatory assist; are still in the evolving phase (see Chapter 5)].

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7 Chapter

Blood Gas and Acid-Base Interpretation

Nitesh Singhal, Praveen Khilnani

Normal pH range of Serum is 7.35-7.45. Low pH means high serum H+ concentration. Low pH in serum (acidemia) is caused by acidosis. Acidosis is a process, if untreated leads to acidemia. High pH (alkalemia) is caused by alkalosis. Thus, acidosis and alkalosis are processes and the terms acidemia and alkalemia describe the state of blood.

ACIDOSIS

Acidosis is defined as serum pH value < 7.34.

Acidosis may be caused by increased arterial partial pressure of CO_2 ($PaCO_2$) (respiratory acidosis),[1] by excess of hydrogen ions by anaerobic metabolism (lactic acidosis), exogenous source (methyl alcohol, ethylene glycol, paraldehyde, and salicylic acid) or excessive bicarbonate loss via kidney or gastrointestinal (GI) tract indirectly causing relative excess of H^+ ions (metabolic acidosis).

Natural compensation of respiratory acidosis is attained by retention of HCO_3 (bicarbonate) by the kidneys in an attempt to normalize the pH. Metabolic acidosis is compensated by hyperventilation to lower $PaCO_2$ and thus, to increase the serum pH. Primary or compensated metabolic acidosis can always be recognized by the pH being low as the compensation process does not bring the pH to completely normal value.

ALKALOSIS

Alkalosis is defined as serum pH greater than 7.45. Excessive bicarbonate administration / reabsorption at renal tubules or loss of H^+ ions via renal or GI tract leads to metabolic alkalosis. Increased pH resulting from low $PaCO_2$ constitutes respiratory alkalosis. Natural compensation of metabolic alkalosis is achieved by hypoventilation and CO_2 retention. Respiratory alkalosis is compensated by increased bicarbonate loss at the renal tubular level.

Respiratory acid-base disorders are usually simple, i.e. either respiratory alkalosis or respiratory acidosis can exist at one time. Metabolic acid-base disturbances are more complex and can coexist at the same time.[2]

BUFFERING SYSTEM

A buffer is a substance that reduces the change in concentration of free H^+ in a solution to which an acid or base has been added. Thus, for example, more

hydrogen ion must be added to a buffered solution to result in a given increase in H^+ than would be required if the solution had no buffer. In a typical patient, there are 30 mEq / L of buffer bases available to buffer hydrogen ions, 75 percent of which is bicarbonate (normal serum concentration of 23 mEq / L).

HOMEOSTASIS

Homeostasis pertains to maintenance of normal biochemical and physiological parameters. In the adult, there is a normal production and excretion of 24,000 nM / day of CO_2. There is also a turnover of hydrogen of 69 mEq / day. Thus, there is constant ongoing acid-base processing: CO_2 is exhaled, and bicarbonate is generated or excreted by the kidney, as necessary. Despite the existence of approximately 105 mEq of hydrogen in the body, there is only 0.0021 mEq of free H^+ in body fluids. The remainder is buffered.

PATHOPHYSIOLOGY

If acidosis occurs, hydrogen ion is buffered; some of the base is lost and a base deficit appears.The maximum possible base deficit is 30. The base must be regenerated to a normal level. The addition of H^+ to the system generates CO_2 and the respiratory rate increases by stimulation of the respiratory center in medulla. The lungs expire the CO_2 and thus affect pH through the Henderson-Hasselbalch relationship:

$$pH = 6.1 + \log \frac{HCO_3}{0.03 \times pCO_2}$$

OR

$$pH = pK \log \frac{\text{bicarbonate}}{\text{carbonic acid}}$$

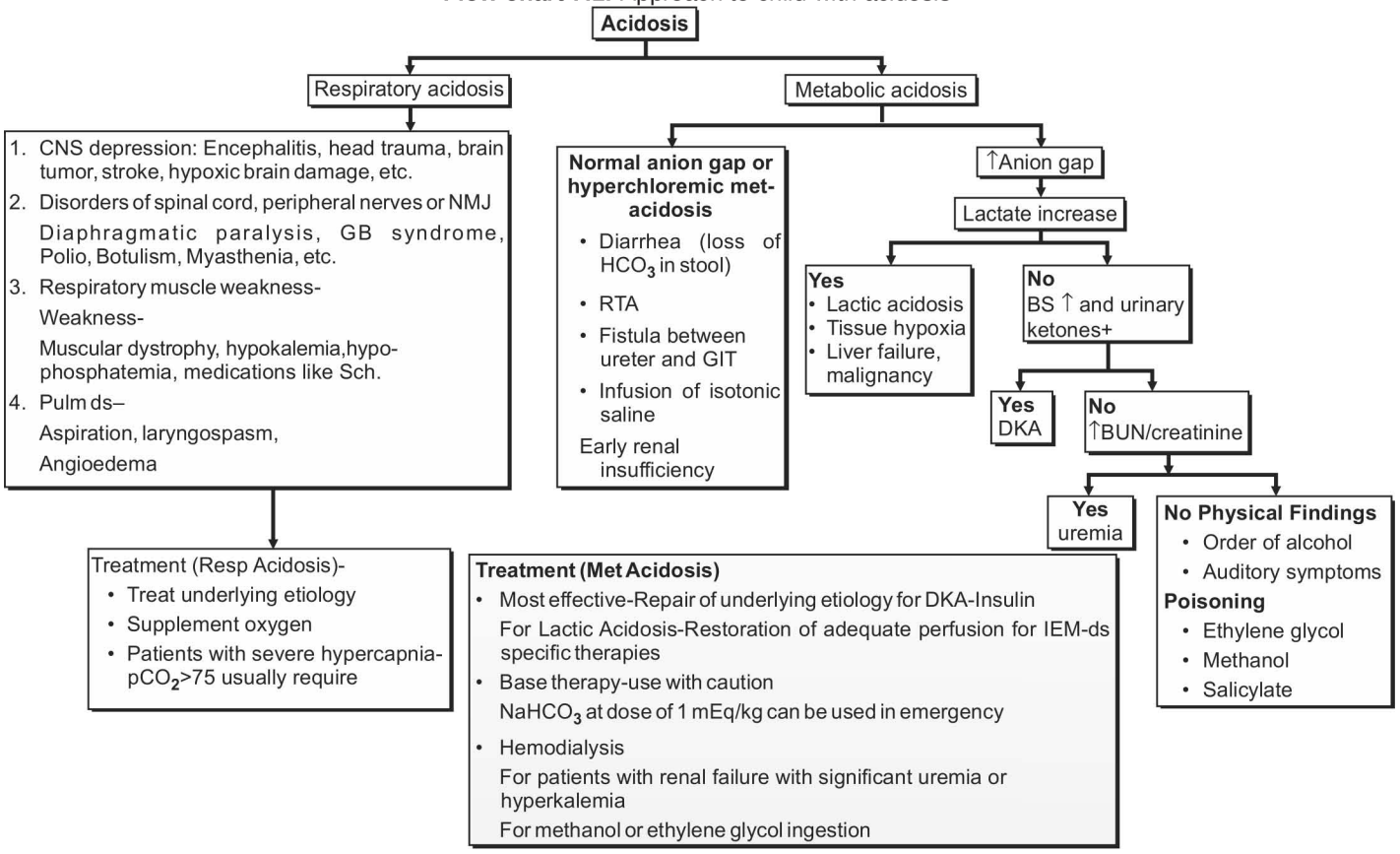
In this equation, pK is the dissociation constant of the carbonic acid (pK = 6.1). Note, however, that although pH is affected, no net loss of H+ occurs. In other words, the respiratory system affects pH through modifications of the major body buffer system (carbonic acid) but can neither excrete H^+ nor regenerate HCO_3. The kidneys control the hydrogen ion and bicarbonate concentrations by regulating bicarbonate reabsorption and by new bicarbonate generation. In addition, the kidneys synthesize ammonia in response to systemic acidosis.

METABOLIC ACIDOSIS (FLOW CHART 7.1)

Metabolic acidosis is a common finding in the pediatric intensive care unit (Box 7.1).

If bicarbonate loss is the cause (e.g. diarrhea with HCO_3 loss, or dilutional acidosis in which bicarbonate is diluted from infusion of nonbicarbonate containing solutions), or if a precursor to hydrochloric acid

Flow chart 7.1: Approach to child with acidosis



BOX 7.1: Etiology of metabolic acidosis

1. Normal anion gap acidosis:
   a. Diarrhea—Small bowel, biliary, or pancreatic tube or fistula drainage. Ureteral diversion with bowel (uretero sigmoidostomy, ileal conduit). Bowel augmentation, cystoplasty
   b. Exogenous chloride containing compounds $CaCl_2$, $MgCl_2$, NH_4Cl, HCl, cholestyramine, arginine HCl parenteral alimentation acidosis
   c. Renal tubular acidosis
   d. Carbonic anhydrase inhibitors acetazolamide, mafenide
   e. Mineralocorticoid deficiency
   f. Dilution (rapid extracellular fluid expansion)
2. Increased anion gap acidosis (normochloremic):
   a. Ketoacidosis: Diabetes mellitus, starvation, glycogen storage disease (type 1) inborn errors of amino acid, or organic acid metabolism
   b. Lactic acidosis: Tissue hypoxia, inborn errors of carbohydrate pyruvate metabolism
   c. Exogenous toxins: Salicylates, methanol, ethylene glycol, paraldehyde
   d. Chronic renal failure.

(Anion gap = Major cations in blood – Major anions in blood)
(Na^+ K^+ – HCO_3^- + Cl^-)

(e.g. ammonium chloride) is added to the system (rare), the chloride will proportionately increase and the anion gap (major cations minus major anions) will be normal.

Conversely, an increase in unmeasured cations will cause an increase in the anion gap. This can be caused by an accumulation of lactic acid, other organic acids, and exogenous acids (ethylene glycol, methanol, paraldehyde, and salicylic acid).

Effects of Metabolic Acidosis

Metabolic acidemia causes decreased myocardial contractility, decreased peripheral resistance, decreased adrenergic-receptor sensitivity, and predisposes to myocardial irritability. It also tends to cause a shift of potassium to extracellular space (hyperkalemia). Clinically, a patient with primary metabolic acidosis is seen with cool extremities, hypotension, lethargy and hyperventilation (to compensate by blowing off CO_2 by lungs and bring the pH to as normal as possible). Expected $PaCO_2$ is determined by the following equation:

$$PaCO_2 = (1.5 \times HCO_3) + 8 \pm 2 \ (1)$$

Values outside this range indicate a mixed disorder.

TREATMENT

Much attention has been paid to the treatment of metabolic acidosis.

A. *Treatment of the underlying cause* is most important, for example, treatment of hypovolemia, shock, poor cardiac output will usually correct acidosis due to above causes.

B. *Alkalinization* of the body with bicarbonate ions has long been practiced. The intent of such a therapy is to reverse the acidemia to allow a return to more normal organ function.This therapy has been criticized for a number of reasons such as a lack of data showing efficacy, worsened blood pressure and cardiac output in certain experimental situations following administration of bicarbonate and use of a systemic base reduces H^+ concentration extracellularly by generating CO_2. This CO_2 readily moves intracellularly and thus, worsens intracellular acidosis.The sodium and osmotic load have also been of concern.

Despite these reservations, bicarbonate therapy is still used cautiously in the patient with severe metabolic acidosis while treatment of the primary cause is ongoing. The dose of bicarbonate is 1 mEq/kg body weight intravenously repeated as needed. When the arterial blood gas (ABG) data is available, the dose of sodium bicarbonate (mEq) is calculated by the formula:

$$0.3 \times \text{wt. in kg} \times \text{base deficit}$$

Pushes of bicarbonate should be avoided due to danger of bradycardia or sudden hypotension. In premature neonates, use of sodium bicarbonate used as intravenous bolus has been associated with increased incidence of intraventricular hemorrhage due to high osmolarity.

An alternative drug to bicarbonate is tris(hydroxymethyl)amino-methane (THAM). Infusion of THAM consumes CO_2, does not have the sodium load, and may penetrate intracellularly more readily. It can cause respiratory depression, hyperkalemia, and hypoglycemia. Dose is 1 mEq/kg given intravenously.

METABOLIC ALKALOSIS (pH > 7.44 BLOOD BICARBONATE > 26 mEq/L) (FLOW CHART 7.2)

Metabolic alkalosis (Box 7.2) in the PICU is most commonly due to iatrogenic fluid depletion resulting in concentration of HCO_3 (concentration alkalosis), increased tubular reabsorption of HCO_3 due to chloride depletion, and loss of potassium thus obligating H^+ loss in the urine (e.g. furosemide therapy). It may also be found as the result of a loss of gastric secretions. Compensatory respiratory acidosis tries to lower the pH to normal. A rise in the pCO_2 can be predicted by the following equation:

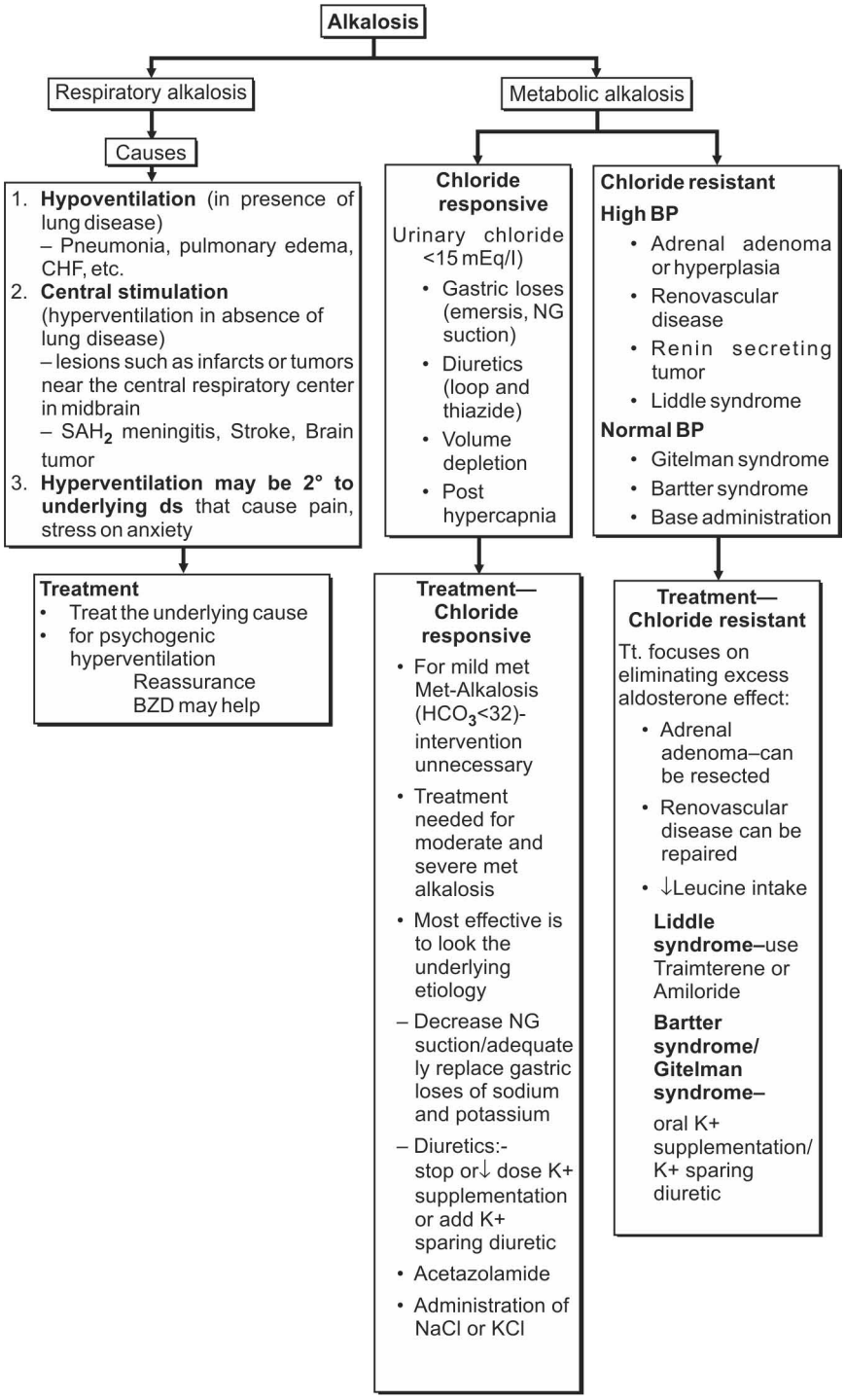
$$\text{Expired } pCO_2 = 0.9 \times HCO_3 + 9 \pm 2^2$$

A value of pCO_2 outside this range is indicative of a superimposed respiratory disorder or additional acid-base abnormality.

Treatment

The treatment of metabolic alkalosis is to correct potassium deficiency and restore fluid volume as appropriate. In patients with metabolic alkalosis due to vomiting or diuretic therapy, treatment with normal potassium chloride usually corrects the alkalosis (Saline responsive alkalosis). If saline therapy does not correct it, mineralocorticoid levels may be high as discussed earlier. Use of spironolactone is indicated. In patients with renal

Flow chart 7.2: Approach to patient with alkalosis



BOX 7.2: Etiology of metabolic alkalosis

Generation of metabolic alkalosis:

A. Loss of H^+ ions
   i. Gastrointestinal
      a. Vomiting
      b. Nasogastric aspiration
      c. Congenital chloride wasting diarrhea
   ii. Renal
      a. Diuretics (thiazides, furosemide, ethacrynic acid)
      b. Excess mineralocorticoid activity
         - Endogenous (hyperaldosteronism, Cushing's disease, adrenogenital syndrome)
         - Exogenous (steroid therapy, licorice, chewing tobacco)
      c. Bartter's syndrome
         - Chloride deficient infant formula
         - Post hypercapnia

B. Gain of HCO_3
   i. Exogenous alkali (HCO_3, citrate, acetate, lactate administration)

C. Contraction of extracellular volume
   i. Chronic diuretic therapy
   ii. Cystic fibrosis (infants)

Maintenance of metabolic alkalosis:

A. Renal failure
B. Extracellular volume depletion
C. Increased mineralocorticoid
D. Potassium depletion
E. Chloride depletion

artery stenosis, angiotensin converting enzyme (ACE) inhibitors (captopril) therapy may be indicated. Patients with Bartters syndrome respond to prostaglandin inhibitors such as Indomethacin (Saline unresponsive alkalosis).[3]

Alternatively, carbonic anhydrase inhibitors (acetazolamide) may be used. For severe cases (myocardial depression assumed to be due to severe metabolic alkalemia), 0.1 normal hydrochloric acid may be used intravenously (rarely required).

RESPIRATORY ACIDOSIS (PH < 7.35 WITH PRIMARY $PACO_2$ > 45 mm Hg)

Respiratory acidosis is characterized by blood gas pH less than 7.35 and a primary increase in $PaCO_2$ (> 45 mm Hg) owing to ineffective alveolar ventilation. Common causes are listed in Box 7.3. An acute increase in pCO_2 is buffered by titration of nonbicarbonate intracellular buffers without significant renal compensation for 12 to 24 hours. The serum HCO_3 concentration rarely rises above 32 mEq per liter during that time. If the serum HCO_3 is greater than 32 mEq per liter, a mixed respiratory acidosis and metabolic alkalosis disorder is likely to occur. With chronic respiratory acidosis (duration greater than 3 days) and metabolic compensation by

BOX 7.3: Causes of respiratory acidosis

Acute and chronic lung disease
- Acute airway obstruction (croup, epiglottitis, foreign body aspiration)
- Bronchospasm (asthma, bronchiolitis)
- Chronic obstructive lung disease (cystic fibrosis, bronchopulmonary dysplasia)
- Interstitial lung disease
- Pneumonia
- Pulmonary edema
- Impaired lung motion
- Pleural effusion
- Pneumothorax.

Thoracic cage abnormalities
- Flail chest
- Scoliosis
- Osteogenesis imperfecta.

Neuromuscular disorders
- Brainstem or spinal cord injury or tumor
- Guillain-Barre'syndrome
- Poliomyelitis
- Myasthenia gravis
- Muscular dystrophy
- Botulism
- Central nervous system depressant
- Drugs (narcotics, sedatives, tranquilizers)
- Pickwickian syndrome (Central hypoventilation syndrome).

the kidneys, serum HCO_3 concentration increases further, but rarely exceeds 45 mEq per liter.

Treatment is to improve ventilation by treatment of primary cause (See Chapters on Mechanical Ventilation, Non-invasive Ventilation, and Tracheostomy).

RESPIRATORY ALKALOSIS (PRIMARY DECREASE IN $PaCO_2$ < 35 mm Hg and pH > 7.44)

A primary decrease in $PaCO_2$ and arterial blood gas pH greater than 7.44 results in respiratory alkalosis. Respiratory alkalosis is probably the most common acid-base disorder among seriously ill patients. The cause is hyperventilation from a variety of sources (Box 7.4). Acutely, the patient may have obvious rapid breathing. When respiratory alkalosis becomes chronic, the respiratory rate may be almost normal with deeper breaths. The initial fall in $PaCO_2$ is acutely titrated by intracellular buffers. Within 1 to 2 days, renal compensation allows the blood gas pH to return towards normal. Metabolic compensation actually returns the extracellular pH to normal in high dwellers and some persons with respiratory alkalosis of longer than two weeks' duration. Increased production of tissue lactic acid was considered potentially important in this process, but measured increases in blood lactate levels have been only 0.5 to 1.0 mEq per liter, an insufficient rise to be significant in normalizing pH.

BOX 7.4: Causes of hyperventilation and respiratory alkalosis

- Anxiety
- Central nervous system disorders (trauma, vascular accident tumor, infection)
- Fever, Sepsis
- High altitude
- Pneumonia
- Pulmonary embolism
- Congestive heart failure with hypoxemia
- Mechanical ventilation
- Salicylates
- Liver failure
- Hyperthyroidism.

Treatment involves treatment of the primary cause, treatment of the underlying pain or anxiety state.

Practical Tips to Approach Acid-Base Disorders

The following questions must be answered before one decides to treat the acid-base disorder:

a. Is this a respiratory or metabolic disorder?
b. Is this a simple or mixed disorder?
c. Is this an acute or chronic disturbance?

The answers are as follows:

a. A respiratory disorder is a primary change in PCO_2 concentration, whereas a metabolic disorder is a primary change in bicarbonate concentration.
b. The simple acid-base disturbance is defined by a primary change in one parameter (PCO_2, or HCO_3). The pH indicates if the disorder is a primary acidosis or primary alkalosis. A mixed acid-base disorder is defined as the coexistence of more than one acid base disorder.
c. An acute disturbance is measured in minutes to hours, but a chronic process lasts days to weeks or longer.[4]

A primary respiratory disorder should be considered if the pH and pCO_2 change in opposite directions. The altered relationship between the magnitude of change in pCO_2 relative to the change in pH indicates the presence of a concomitant metabolic disorder, or an incomplete compensatory response.

The pH changes 0.008 units for every 1 mm Hg change in acute uncompensated acidosis. pH changes only 0.003 units for every 1 mm Hg change in pCO_2 in the presence of chronic compensated acidosis.

In the presence of partially compensated respiratory acidosis, the pH changes between 0.003 to 0.008 for every 1 mm Hg change in pCO_2 (Table 7.1).[5]

Regardless of the respiratory acidosis being uncompensated or partially compensated, if the pH is below normal and the pCO_2 is elevated, the primary disorder is respiratory acidosis.

TABLE 7.1: Respiratory acidosis interpretation

pH change (below normal)	*pCO_2 change (above normal)*	*Diagnosis*
> 0.008	1 mm Hg	Associated metabolic acidosis
0.003 to 0.008	1 mm Hg	Partially compensated respiratory acidosis
< 0.003	1 mm Hg	Associated metabolic alkalosis

Modified from Marino P: Algorithms for acid-base interpretations. In: The ICU Book. Marino P (Ed): Malvem, Lea & Febiger, 1991;415.

TABLE 7.2: Interpretation of respiratory alkalosis

pH change (above normal)	*pCO_2 change (below normal)*	*Diagnosis*
> 0.008	1 mm Hg	Associated metabolic alkalosis
0.002-0.008	1 mm Hg	Partially compensated respiratory alkalosis
< 0.002	1 mm Hg	Associated metabolic acidosis

Modified from Marino P: Algorithms for acid-base interpretations. In: The ICU Book. Marino P (Ed.): Malvem, Lea & Febiger, 1991;415.

During acute uncompensated respiratory alkalosis, the serum pH increases 0.008 units for every 1 mm Hg decrease in pCO_2. However, during chronic compensated respiratory alkalosis, the serum pH increases only 0.002 units for every 1 mm Hg decrease in pCO_2 (Table 7.2).

MIXED ACID-BASE DISORDERS

A mixed acid-base disorder is defined as the coexistence of more than one acid-base disorder.

Mixed Metabolic and Respiratory Acidosis

Plasma bicarbonate concentration is low and pCO_2 value is high. Because of the coexistence of these two acidotic disorders, the pH value is significantly decreased. Common examples of mixed metabolic and respiratory acidosis are cardiopulmonary arrest, adult respiratory distress syndrome and septic shock, asthma and lactic acidosis due to increased work of breathing.

Mixed Metabolic and Respiratory Alkalosis

A mixed metabolic and respiratory alkalosis is defined when the plasma bicarbonate is high and the pCO_2 is low.[3] These acid-base disorders may be present in children with respiratory alkalosis associated with congestive heart failure and diuretic therapy.

Mixed Metabolic Alkalosis and Respiratory Acidosis

These disorders show high plasma bicarbonate and excessively high pCO_2 (above the normal compensatory mechanism). These acid-base distur-

bances are commonly seen in patients with bronchopulmonary dysplasia and diuretic therapy. Similarly, patients with chronic respiratory failure and excessive gastric drainage through nasogastric tube, may present with these disorders.

Metabolic Acidosis and Respiratory Alkalosis

A diagnosis of mixed metabolic acidosis and respiratory alkalosis can be made when both plasma bicarbonate and pCO_2 are seriously low (above the normal compensation), and the pH is normal or near normal.

This acid-base disorder may be associated with rapidly corrected metabolic acidosis, salicylate intoxication and in the hepatorenal syndrome.

Treatment

Therapy must be directed to correct the precipitant factors, and, each acid-base disturbance needs specific therapy. For example, in a dehydrated child with metabolic acidosis and respiratory acidosis, the therapy must include fluids and bicarbonate to treat the metabolic acidosis, and ventilatory support to correct the respiratory acidosis.

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8 Chapter

Care of the Ventilated Patient

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Care of a patient, especially mechanically ventilated patient, needs a team approach. In the western world and in some tertiary care centers in India, this team consists of the physician, the nursing staff, physiotherapists and respiratory therapists (RT). In majority of the centers in India however, there is no role played by RT. Their services are usually provided by the staff nurse and at some centers by physiotherapists. Our nurses are often overworked and may be providing care for more than one patient. The cost of care in the ICU is also very high and hence needless procedures and practices are best avoided. It becomes imperative that we judiciously use the time of our personnel and follow as much of evidence-based medicine as possible. Majority of the practices that we follow in our day-to-day life in the ICU have very few trials, if any supporting its use.

This chapter will try to provide evidence for various practices such as humidification, positioning, physiotherapy, suctioning, nebulization as in an intubated patient.

PHYSIOTHERAPY

Despite the extensive use of chest physiotherapy in pediatric practice, there is very scant information available on its use in mechanically ventilated children. There is very little evidence for the beneficial effect of chest physiotherapy (CPT). Its use is well-established only in acute atelectasis and pediatric lung abscess in children greater than 7 years.[1-3] Prolonged immobilization and supine positioning leads to atelectasis especially of the left lower lobe, due to the weight of the heart. This in turn leads to retention of secretions, super added bacterial infection and nosocomial pneumonia.

The physiological rationale behind CPT is to mobilize secretions, prevent pneumonia and reduce hospital stay. CPT consists of a series of maneuvers such as positioning, percussion, vibration and manual hyperinflation.[1,2]

Positioning

In order to increase drainage of secretion, improve ventilation/perfusion (V/Q) matching, improve oxygenation, decrease work of breathing and increase functional residual capacity (FRC) certain body positions are

utilized in the ICU. These include the upright posture in a child who has obesity, ascites, abdominal surgery, or the 45° angle to decrease the risk of aspiration in a child receiving enteral feeding.

A child with unilateral lung disease is to be placed with the affected lung uppermost in order to improve drainage of secretion and also for a better V/Q matching[4] (as both perfusion and ventilation will increase in the gravitationally assisted normal lung).[1,2,5] One should however remember the risk of suppurative secretions draining into the normal lung and worsening the disease process. Prone positioning has been shown to improve oxygenation in up to 85 percent of patients in the early stages of ARDS by increasing FRC, increasing V/Q matching, enabling drainage of secretions and improving lymphatic drainage.[6-9]

Percussion and Vibration

Percussion is performed by manually clapping the chest wall using cupped hands.[3,10] It is done to mobilize secretions from the nondependent areas of the chest to the central airways from where they may be suctioned. Vibration and percussion can be done mechanically as well. Vibration is generally used in neonates to avoid damage to their fragile chest walls.

Manual Hyperinflation

It is usually performed before and between suctioning to prevent hypoxemia while suctioning. The patient is disconnected from the ventilator and is bagged with a resuscitator bag using slow deep inspiration, inspiratory hold and quick release to enhance expiration. This causes the recruitment of atelectatic segments and also mobilizes secretions.[1,2]

Continuous Rotational Therapy

This involves the use of specialized beds that continuously turn the patient along a longitudinal axis.[1,10] It is currently unavailable in India.

Fiberoptic Bronchoscopy (FOB)

This is used for removal of retained secretions and for suctioning thick tenacious mucus plugs. Despite its widespread acceptance for removal of secretions, its superiority over chest physiotherapy has not been proven. Despite this, one should consider FOB in lobar or greater atelectasis in patients not responding to vigorous chest physiotherapy or in life-threatening whole lung atelectasis.[11]

Complications

Chest physiotherapy is associated with increased incidence of hemodynamic disturbances, higher incidences of gastroesophageal reflux,[1,2] elevation of intracranial pressure and increase in oxygen consumption.[12-14] To some extent, the effect on intracranial pressure and hemodynamics can be decreased by prior sedation and muscle relaxation of the patient. The head

down positioning while doing rigorous physiotherapy is likely to increase the risk of aspiration and worsening of intracranial pressure. Neonates and children with fragile bones, such as in rickets and osteogenesis imperfecta, can develop rib fractures.

Currently, there is very little data supporting the use of CPT for any condition other than atelectasis. Positioning is useful in ARDS and in individuals with unilateral lung disease. Studies, however reveal that continuous rotational therapy and kinetic percussion[10] decreases pulmonary complications. Studies done in adults show that chest physiotherapy fails to decrease the length of hospitalization, length of fever[1] or duration of ventilation. Despite the rationale for its use, CPT has not been shown to hasten the recovery from pneumonia or decrease the duration of hospitalization.[15]

Humidification

Normally, the upper airway of a person heats and humidifies the atmospheric air to body temperature and 100 percent relative humidity. Medical gases have no humidity and bypassing the upper airway as in patients with artificial airway such as endotracheal tube or tracheostomy makes humidification a must.[16,17] Decrease in the humidity can lead to mucosal damage and tube occlusions, atlectasis, loss of FRC, hypoxia and increased incidence of pneumonia. Excessive humidification is also a problem and can decrease mucociliary clearance, cause hyperhydration and loss of surfactant activity. Humidification can be achieved using heated water humidifier (HW),[16,17] heated wire or by Heat and Moisture Exchange (HME) filters. The appropriate temperature and humidity to be used in ventilated patients has not yet been established (Refer to Appendix).

Heated Water Humidifiers (HWHs)

Heated humidifiers use heating elements to increase the temperature of water and humidity of the inspired gas.[18] The degree of humidification of the inspired gas will depend on the temperature setting, flow rate, water level in the humidifier and the length of the circuit. These generally bubble the inspired gas through the column of water. These are to be used only with a high flow system such as that needed during mechanical ventilation. The temperature of the inspired gas has to be monitored in order to avoid overheating and tracheal burns.

Heated Wire Circuit

In an attempt to decrease the rainout associated with heated water humidifier, heated wire circuit is available. This is available in both reusable and disposable form. The temperature of the gas is maintained at a select value.

Heat and Moisture Exchangers (HMEs)

HME filters combine humidifying properties[19,20] of plastic foam impregnated with hygroscopic substance, with bacterial filtering properties

of filter membrane. HME filters are made of substances with low thermal conductivity such as ceramic, polyurethane, polyethylene or cellulose sponge material.[21] The hygroscopic substance can be Calcium chloride, Magnesium chloride, Aluminium chloride or Lithium chloride.[19] It chemically absorbs water vapours in expired gas, which then saturates the inspired gas. HME has been found to provide safe and adequate humidification of inspired gases. Some of the filters available in the market claim to be 99.5 percent efficient in its filtration properties. A recently done study, however, casts doubts about this claim. Their use, however, is associated with lesser circuit contamination. There has not been any statistical difference in the incidence of ventilator associated pneumonia (VAP) with the use of HME filters. Its use can increase dead space and resistance, which may be overcome by increasing pressure support. It can be used safely up to a week[20,22] or until visible liquid contamination occurs. This gets converted to cost saving on disposables, fewer need for breaking the circuit and hence, reduction in bacterial contamination.

Aerosol Therapy

Aerosol is a group of particles suspended in air for a relatively long time. Aerosol therapy is used in order to deliver the drug directly to the site of action, thereby minimizing the systemic side effects and improving the efficacy. The size of the aerosol is expressed as mass median aerodynamic diameter (MMAD). The MMAD determines the rapidity with which the aerosol will settle in the airway. Aerosol gets deposited through the process of impaction, sedimentation and diffusion.[23,24] In order to be maximally effective, the aerosol particles should be 0.5-5 μm in size. Particles larger than 3 μm get impacted by its size on the tubing and endotracheal tube. Particles around 2 μm get sedimented due to gravity and still smaller particles undergo diffusion.

Aerosol therapy may be provided using nebulizers or Meter dose inhalers (MDI). MDI's are as efficient and according to some studies more efficient than nebulizers. The latter, however, has a greater versatility and can be adapted to deliver various drugs.

An array of drugs like bronchodilators, steroids, antibiotics, anticholinergics, mucolytics, prostacyclin, etc. get delivered by the nebulizer route. The most common drug however is bronchodilator and steroids.

The amount of the drug deposited in the lower airway will depend on several factors such as physiochemical properties of the drug,[23-25] the nature of the device, position of the device in the circuit, the nature of the ventilator circuit, ventilatory parameters, humidity and density of the inspired air and on the airway anatomy.

Characteristics of Aerosol Generating Device

Greater respiratory tract deposition occurs when the MMAD of the aerosol is in the range of 1-3 mm. The larger size particle can get impacted in the endotracheal tube and in the ventilator circuit.[23,26] A nebulizer could have

continuous or intermittent operation. Continuous operation requires the nebulizer to be driven by a pressurized gas source. Intermittent operation requires a separate line from the ventilator to drive the nebulizer during inspiration. Between the two, intermittent operation during inspiration is preferred as it lowers the wastage of drug.

Ventilatory Parameters

Adequate aerosol delivery is achieved in assisted modes of ventilation only if the patient is in synchrony with the ventilator. 20 percent more delivery can be achieved during CPAP mode than with volume cycled breaths.[23,27,28] The tidal volume has to be higher than normal to compensate for the compressible volume of the tubing. Longer inspiratory time has to be used in order to increase the nebulizer generated aerosol to be inhaled with each breath. This is needed even in an MDI generated aerosol although the mechanism is not clearly known.

Circuit Characteristics

In general, smaller endotracheal tube, narrow internal diameter of the pediatric ventilatory circuit and humidification of gases[1,29] all reduce the aerosol deposition in the lung. Lower density gas such as heliox mixture enable better deposition of the aerosol by decreasing the turbulence of air flow.

Position of the Device

Aerosol delivery to the patient is improved by placement of a nebulizer at a distance of 30 cm from the endotracheal tube[26,29] rather than between the patient wye and the endotracheal tube because the ventilator tubing acts as a spacer for the aerosol to accumulate between breaths.

Suggested Method for Delivery of Drug by Nebulization (Modified from Recommendations by Hess[30])

1. Clear secretions from ET tube.
2. Ensure a high tidal volume to eliminate the dead space of the tubing.
3. Decrease the inspiratory flow rate so that the inspiratory time is prolonged.
4. Ensure 4-6 ml of volume in nebulizer and place the nebulizer in the inspiratory limb 30 cm from wye connection.
5. Ensure air-flow of 6 L/min to run nebulizer.
6. Nebulize solution only during inspiration.
7. Tap nebulizer intermittently during operation.
8. Disconnect nebulizer from the circuit after use.

Meter Dose Inhaler (MDI)

Only 1 percent of the content of MDI is the active drug. The rest is made up of propellants and preservatives. The amount of the drug delivered by

MDI is much smaller than the nebulizer.[23,31] MDI may be used directly on ET tube or through a chamber. A variety of chambers are available for use of MDI during mechanical ventilation. As a rule, it is better to use a chamber device than to use MDI directly on the ET tube. The chamber could be collapsible or non-collapsible and be attached to the inspiratory limb of the ventilator circuit.[23] It is preferable to use a collapsible chamber that does not have to be disconnected from the circuit between uses. It is important that the actuation of the MDI is synchronized with the inspiratory time. An aerosol cloud enhancer spacer directs the fumes away from the patient into the spacer.[32,33] The drug then gets carried to the patient during the inspiratory flow. Thus, this method of delivery is the most efficient.

Suggested Method of Aerosol Delivery by MDI (Modified from Recommendations by Hess[30])

1. Clear secretions from ET tube.
2. Ensure a high tidal volume to eliminate the dead space of the tubing.
3. Decrease the inspiratory flow rate such that the inspiratory time is prolonged.
4. Place the acturator- spacer device in the inspiratory limb of ventilator.
5. Shake the MDI and place on the spacer.
6. Discharge MDI at the onset of inspiration.
7. Repeat 20 to 30 seconds later.

Several studies have compared the efficacy of nebulizer and MDI.[26,28] The properly executed MDI may be better than nebulizer. The bio-availability is very poor when one uses the right angle MDI port and hence, should not be used to deliver bronchodilator in mechanically ventilated patients.

Of all the medicines used, bronchodilators are the ones that are most commonly delivered as an aerosol. Bronchodilators are used in an asthmatic. In order to reduce air trapping, the ventilatory parameters one uses is almost exactly the opposite to the parameters that one has to use for optimization of aerosol delivery. Furthermore, humidification is not possible while using aerosol. All this makes it difficult, wasteful and even harmful to use continuous aerosol therapy while on ventilator.

Mucolytics

There are no randomized control trials. However, there have been case reports in the use of N-acetylcystine and DNase in life-threatening situations of mucous plugs.[11,23] N-acetylcystine works by breaking the disulphide bonds in the mucus and hence making it less viscid and easier to suction. N-acetylcystine installation has been associated with bronchospasm, which can be overcome by using β_2 agonist nebulization. Although DNase is used in patients with cystic fibrosis, it is not routinely used for removing secretions. Its use has been described in neonates and asthmatics with life-threatening mucous plugs. It is expensive and not available in India.

Endotracheal Suctioning

Suctioning can be done using the closed or open suctioning system. In closed suction system, the suction catheter is encased in a plastic sleeve and is a part of the ventilatory tubing. The advantage of the closed suctioning system is that cost of disposable is reduced; intuitively the risk of infection has to be less (although there is no proof). The PEEP effect is not lost while suctioning and hence the risk of hypoxemia in patients with reduced FRC is less.[25] Its disadvantage is that resistance can be increased and it decreases the pulmonary bio-availability of β_2 agonist when used in asthmatics. In order to decrease the viscidity of secretion when not contraindicated, we increase the fluid administration to the patient, i.e. hyperhydrate the patient. In some institutions, normal saline installation into the ET tube is routinely practiced. We use it when the secretions are viscid and copious. In Western countries, more institutions have started using 3% saline. While suctioning, it is important to remember that mucosal injury can occur. Hence, gentle suctioning taking care not to push the catheter up to the carina is a must.

Personally in our ICU we use the closed system in ARDS. In patients with pulmonary hypertension and elevated intracranial pressure, sedation prior to suctioning is a must[34] as significant elevations of pressures and deterioration of hemodynamic parameters can occur.

Eye Care

A ventilated patient is often heavily sedated and may be even muscle relaxed. This predisposes the individual to exposure keratitis, corneal ulceration and infection. Along with passive closure of the eyelid, using lubricants at scheduled intervals has been shown to provide protection from above mentioned problems. The exact lubricant and the number of times to use it have not been established. We use artificial tears every two hours and if we use an oily lubricant apply it four times a day.

In conclusion, except for a few practices that we use in day-to-day in the ICU, most methods are not proven to be effective. We should not let our practices be guided by hearsay and should practice evidence-based medicine as often as possible.

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APPENDIX:
Humidification and Mechanical Ventilation

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INTRODUCTION

Humidification of respired gases during mechanical ventilation is a standard of care. Delivery of cool, anhydrous gases from institutional compressed air and liquid oxygen systems to the patient with an instrumented airway, bypassing the normal mechanisms of warming and humidification, has dire consequences.

The addition of heat and moisture to inspired gases delivered to the patient during mechanical ventilatory support via an artificial airway is known as **humidification.** There is agreement among clinicians that heating and humidifying inspired gases is required. The level of heat and humidity, type of device, duration of use, impact on ventilator-associated pneumonia and optimal characteristics, however, are widely debated. Clinical decision-making regarding the use of humidification devices requires an understanding of pathophysiology and equipment. Clearly, the selection of the device to be used on a given patient must be based on the patient's lung disease, ventilator settings, intended duration of use, and other factors (e.g. the presence of leaks and body temperature).

A lot has changed over the last few years. It is now not considered whether gases delivered to patients should be humidified, but by how much (optimum humidity); not whether we should be concerned about removal of microbes from gases delivered to patients, but what level of performance can be expected from the devices in use.

In general, the artificial humidification process can be described by two means:

- Determining the moisture output of the humidifying device.
- Determining the water loss from the airways using the humidifying device.

PHYSIOLOGY

The main function of upper airway is to condition inspired gases so that when they reach the alveoli, they are warm, humidified, and free of foreign material. The mucociliary elevator on the inner surface of the highly vascular mucosa lining the airway is responsible for this specialized function. Ambient air inspired through the nose and upper airway is heated to 37°C and humidified to 100% relative humidity.

The nose and upper airway act as an efficient countercurrent heat and moisture exchanger that conditions inspired air and retains heat and moisture on expiration. There is a point below the carina in the upper airway, the isothermal saturation boundary (ISB), at which inspired air reaches body temperature and 100% relative humidity. Above the ISB, the airway acts as a heat and moisture exchanger; below it temperature and humidity remain constant. The exact position of the ISB varies slightly according to the volume, temperature, and relative humidity of inspired air.

When the upper airway is bypassed by an artificial airway (tracheal tube or tracheostomy), air or medical gases are delivered directly into the trachea. The ISB may be shifted down, i.e. at level of 3rd subsegmental bronchi or may be up according to the amount of heat and moisture present in the inspired gases; hence the airway structure or function may be modified. Even in extreme conditions, however, it does not fall to the level of the respiratory bronchioles or alveoli, so that gas in the functional residual capacity of the lungs has a stable water content and temperature that is in equilibrium with blood and tissues.

Under normal conditions, about 250 ml of water are lost from the lungs each day to humidify inspired gases.

It generally is accepted that tracheal intubation, mechanical ventilation, and anesthesia may damage the respiratory epithelium and alter mucociliary function. These abnormalities have been attributed notably to local trauma caused by:

- Tracheal tube or suction catheter
- Drugs
- High oxygen concentrations
- Local inflammatory phenomenon
- Infection
- The pressure effect of mechanical ventilation.

Therefore, during ventilation of intubated or tracheostomized patients, the gases entering the trachea should mimic physiologic conditions as closely as possible. Box A8.1 gives information on consequences of ventilation without conditioning of inspired medical gases.

BOX A8.1: Consequences of ventilation without conditioning of inspired medical gases

Cytomorphological airway modifications:

- Decrease in sol phase depth
- Hyperviscosity of airway secretions
- Tracheal inflammation
- Deciliation, epithelial ulceration, and then necrosis.

Functional airway modifications:

- Decrease in the humidification capabilities
- Downward shift of ISB (Isothermal saturation boundary)
- Decrease in mucus transport velocity, secretions retention
- Decrease in bronchospasm threshold
- Alteration of the ciliary function, ciliary paralysis
- Airway obstruction and increase in airflow resistance.

Pulmonary, mechanical and functional alterations:

- Atelectasis
- Decrease in FRC and compliance
- V/Q mismatching, increase in intrapulmonary shunting, hypoxemia
- Pulmonary infection.

DEVICES FOR HUMIDIFICATION OF INSPIRED GASES

Devices that are used for humidification of inspired gases must ensure physiologic conditions in the respiratory tract. This means that pulmonary water losses of greater than 7 mg/L that are due to ventilation with dry gases should be avoided as well as ventilation with oversaturated gases or gases that are warmer than body temperature. It should be taken into account that all systems that are used for this purpose, influence the inspiratory and expiratory resistance as well as the functional dead space in different ways. This is especially important in spontaneously breathing patients to avoid hypercapnia and additional work of breathing. Therefore, the additionally imposed inspiratory and expiratory resistance of the system must be known. Similar to the added resistance, the increased functional dead space that is caused by addition of a humidifying device (e.g. HME) must be considered when used with patients who are unable to compensate by increasing their ventilation, which thereby causes CO_2 accumulation.

Types of Humidifiers

Active humidifier: Adds water vapor and heat to the inspired gases (e.g. heated humidifiers).

Passive humidifier: Uses exhaled heat and moisture to humidify inspired gases (e.g. HMEs).

Devices for Nonintubated Patients

Spontaneously breathing patients without a tracheal tube or tracheostomy necessarily do not require additional strategies for conditioning of respiratory gases. But because of the subjectively unpleasant concomitant phenomena that are due to the respiration of dry gases by way of a facemask or oxygen tubing, it is advisable to humidify the gases to normal conditions.

Devices for Intubated Patients

- Heat and moisture exchangers
- Humidification.

Simple Humidifiers

These do not employ heat and the amount of water added to the inspired gas is inadequate for intubated patients. Simple humidifiers operating at 20°C and 100% relative humidity deliver only 17 mg water/L of gas. In distal trachea, gas should contain 37 mg water/L. This difference should be now supplied by airway epithelium leading to loss of heat and water from epithelium and thereby its drying.

Type	*Method of humidification*	*Efficiency*
Pass-over	Gas flows over the surface of the water and then to the patient	Low
Bubble	Gas flows through a diffuser into water, generating bubbles that increase the surface area for humidification; gas then flows to the patient	Moderate
Jet	Gas flow produces an aerosol that disperses water particles into the gas stream, increasing the surface area for humidification. Baffles prevent delivery of particulate water to the patient	High

Heated Humidifiers

These deliver more water to airways by heating the inspired gas. The temperature of gas that is delivered to the patient is regulated by a servo device that measures gas temperature at airway and adjusts the heater output of the humidifier. These are used when gases are being delivered via an artificial airway and mechanical ventilator.

Heating the water causes a larger number of water molecules to gain sufficient kinetic energy to enter the gaseous state, thereby the vapor content of inspired gas is increased.

Type	*Method of humidification*	*Efficiency*
Cascade	Gas is forced through a grid that is covered by a film of heated water. The froth that is generated humidifies the stream of gas to the patient. Gas temperature delivered to the patient can be regulated by a servo.	High
Bubble	Gas flows through a diffuser into heated water, generating bubbles that increase surface area for humidification. The heated and humidified gas then flows to the patient.	High
Wick	Gas flows past wick (blotting paper or sponge) that remains saturated with water by capillary action. The wick is surrounded by heaters. Wick humidifiers do not bubble gas through water or grids and have a very low resistance to flow.	High

Heat and Moisture Exchangers (HMEs)

Placed on the distal end of the tracheal tube, HME's store a portion of the humidity from the expired volume and return this to the inspired air. They function as passive respiratory air humidifiers, which do not depend on a supply of external energy or source of water. Because their mode of operation is related to the nasal operating principle, they also are called ''artificial noses''. An HME can only return as much heat and humidity as has been stored reversibly from the previous breath. Therefore, the quantity of inspiratory humidity is determined by the moisture content of the expired air, which is defined by the patient temperature, and by the thermodynamic properties of the HME materials (specially designed paper, cellulose or polyurethane foams).

To improve the heat- and moisture-conserving qualities of the HME material, a hygroscopic coating, such as magnesium, calcium, or lithium chloride, is used. These compounds reversibly adsorb water molecules and thus increase the water retention capacity. After a few breaths, HMEs are at almost full effectiveness and reach steady state within a few minutes. Subsequently, the moisture-returning properties of the HMEs depend only on ventilatory parameters, the most important of which is tidal volume, such that the moisture-returning performance decreases as the tidal volume increases.

HMEs always result in an elevation of the inspiratory and expiratory airway resistances; this should be considered especially in cases that involve spontaneous respiration. The internal volumes of HMEs should be as small as possible so that they do not increase the effective dead space too much. A combination of HMEs and catheter mounts results in a further increase in the dead space, and therefore, must be considered critically, especially in cases that involve spontaneous respiration. If a catheter mount is necessary to add flexibility to the breathing system, the HME preferably should be connected directly onto the tracheal tube with the catheter mount behind it; otherwise, the humidification efficiency of the HME will be reduced by condensation in the catheter mount. Children should be ventilated with special HMEs that have a small internal volume.

Contraindications for Use of an HME

- Patients with thick, copious, or bloody secretions.

- Patients with an expired tidal volume less than 70% of the delivered tidal volume (e.g. those with large bronchopleurocutaneous fistulas or incompetent or absent endotracheal tube cuffs).
- Patients with body temperatures less than 32°C.
- Patients with high spontaneous minute volumes (> 10L/min).
- An HME must be removed from the patient circuit during aerosol treatments when the nebulizer is placed in the patient circuit.
- Non-invasive ventilation.

Hazards and complications associated with the use of humidification devices include:

- Hypothermia and/or hyperthermia.
- Thermal injury to the airway from heated humidifiers; burns to the patient and tubing meltdown if heated-wire circuits are covered or circuits and humidifiers are incompatible.
- Underhydration and impaction of mucus secretions.
- Hypoventilation and/or alveolar gas trapping due to mucus plugging of airways.
- Possible increased resistive work of breathing due to mucus plugging of airways.
- Possible hypoventilation due to increased dead space (HME).
- Inadvertent overfilling resulting in unintentional tracheal lavage (heated humidifiers).
- The fact that when disconnected from the patient, some ventilators generate a high flow through the patient circuit that may aerosolize contaminated condensate, putting both the patient and clinician at risk for nosocomial infection (heated humidifiers).
- Inadvertent tracheal lavage from pooled condensate in patient circuit (heated humidifiers).
- Elevated airway pressures due to pooled condensation (heated humidifiers).
- Patient-ventilator dysynchrony and improper ventilator performance due to pooled condensation in the circuit (heated humidifiers).
- Ineffective low-pressure alarm during disconnection due to resistance through HME.

The following variables should be recorded during equipment inspection:

- Humidifier setting (temperature setting or numeric dial setting or both): During routine use on an intubated patient, a heated humidifier should be set to deliver an inspired gas temperature of 33 ± 2°C and should provide a minimum of 30 mg/L of water vapor.
- Inspired gas temperature: Temperature should be monitored as near the patient's airway opening as possible, if a heated humidifier is used.
- Specific temperatures may vary with patient condition, but the inspiratory gas should not exceed 37°C at the airway threshold.
- When a heated-wire patient circuit is used (to prevent condensation) on an infant, the temperature probe should be located outside the incubator or away from the direct heat of the radiant warmer.
- Alarm settings (if applicable): High temperature alarm should be set no higher than 37°C, and the low temperature alarm should be set no lower than 30°C.
- Water level and function of automatic feed system (if applicable).
- Quantity and consistency of secretions. Characteristics should be noted and recorded. When using an HME, if secretions become copious or appear increasingly tenacious, a heated humidifier should replace the HME.

Reusable heated humidifiers should be subjected to high-level disinfection between patients. Clean technique should be observed when manually filling the water reservoir and sterile water should be used. Condensation from the patient circuit should be considered infectious waste and disposed of according to hospital policy using strict universal precautions. Because condensate is infectious waste, it should never be drained back into the humidifier reservoir.

HUMIDIFICATION DEVICES AND VAP

Breathing systems used with heated humidifiers are associated with a rapid and high level of bacterial colonization. This colonization is considerably reduced with the use of HMEs. They do not need to be changed during the entire ventilation period of a given patient unless they are visibly soiled or mechanically malfunctioning. The incidence of VAP is not influenced by the type of humidification device (heated humidifier or HME) or by the duration of use of HMEs or the type of HME, but prolonging the use of a HME further reduces the risk of cross-contamination and results in considerable cost savings. Because breathing systems become rapidly and heavily contaminated when used with heated humidifiers, even with the use of heated delivery tubes and because HMEs efficiently prevent this contamination, some people strongly believe that HMEs should be preferred to heated humidifiers in a global policy against nosocomial infection and cross-contamination.

In addition, there are now substantial data indicating that HMEs can be used as efficiently as heated humidifiers for long-term mechanical ventilation of most ICU patients with exceptions being small infants, thick secretions, spontaneously breathing. This policy reduces staff workload, reduces the potential risk of cross-contamination, and enables substantial cost savings. Flow chart A8.1 gives information on choosing humidification devices in ICU.

SUMMARY

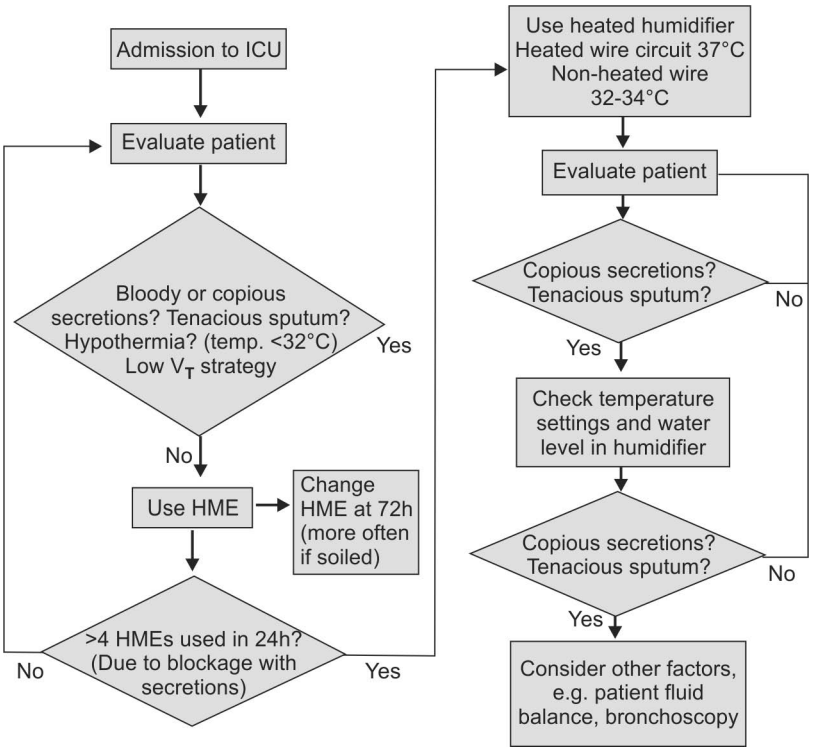
Heat and Moisture Exchangers

The basic principle of HMEs were described in the late 1960s but have undergone considerable development since the end of 1970s.[2-4] Purely Hydrophobic were among the first HMEs to be developed. They possess very high antibacterial properties but perform poorly in terms of humidity output and have been responsible for endotracheal occlusions.[5-8] Hygroscopic HMEs have better performance than the hydrophobic HMEs but do not possess antibacterial filtration properties. Lastly, more recent HMEs comprise together hydrophobic and hygroscopic properties and therefore, exhibit both humidifying and antibacterial filtration properties.[9-12] HME filters combine humidifying properties of plastic foam impregnated with hygroscopic substance, with bacterial filtering properties of filter membrane.[13,14] HME filters are made of substances with low thermal conductivity such as ceramic, polyurethane, polyethylene or cellulose sponge material.[15] The hygroscopic substance can be Calcium chloride, magnesium chloride, aluminium chloride and lithium chloride. It chemically absorbs water vapors and heat energy in expired gases which then saturates the inspired gas.

Contraindications of HME

- Thick, copious and bloody secretions

Flow chart A8.1: Algorithm for choosing humidification devices in ICU



- If expired tidal volume is less than 70% of the delivered tidal volume, e.g. those with large bronchopleurocutaneous fistulas or incompetent or absent endotracheal tube cuffs
- Body temperature less than 32°C
- High spontaneous minute volumes less than 10 L/min.

Advantages of HME

- Inexpensive
- Small, light weight units
- Easy to use and low maintenance
- Reliable and consistent performance
- No external source and power monitoring required
- Ideal for transferring patients
- Bacterial and viral filtration
- Low resistance when dry
- Disposable
- Provide absolute humidity of more than 30 mg/L.

Disadvantages of HME

- Limited humidification efficiency, varying widely between models and brands
- No significant temperature conservation
- Increased dead space
- Increased work of breathing

- Increased intrinsic peep
- Potentials for leak and disconnections
- Sputum, blood or pulmonary edema fluid can cause partial obstruction of the HME with significant elevation of the airway resistance.

Heated Water Humidifiers

HH use heating elements to increase the temperature of water and humidity of the inspired gas.[16] The degree of humidification of the inspired gas will depend on the temperature setting, flow rate, water level in the humidifier and the length of the circuit. These gradually bubble the inspired gas through the column of water. They are simple, comprehensive and disposable but they are inefficient with a maximum absolute humidity of 9 mg/L. Their use is restricted to deliver supplementary oxygen via a face mask or nasal cannula.

Disadvantages

- Bulky, complex pieces
- High maintenance costs
- Increased incidence of bacterial colonization of the water reservoir and delivery tubing
- Overhydration, water aspiration, scalding of the airway, electrocution and thermal damage to the tubing
- High humidity can also damage the breathing system and can block the sidestream capnography monitoring.

Heated Wire Circuits

In an attempt to decrease the rainout associated with heated water humidifier, heated wire circuit is available. This is available in both reusable and disposable form. The temperature of the gas is maintained at a select level.

COMPARISION OF HMEs AND HWHs IN THE ICU

There is controversy regarding the most suitable device and optimal level of humidification required for the mechanical ventilation of critical care patients. The evidence is limited and meta-analyses have failed to establish a significant difference in mortality, duration of mechanical ventilation, length of stay, incidence of airway occlusion.[17,18] Active humidification with heated humidifiers (HHs) has long been considered the gold standard for adequate inspired gas conditioning, since these devices can theoretically deliver gas at 37°C with 44 mg H_2O/L absolute humidity to the patient.

Passive humidification with heat and moisture exchangers (HMEs) has generally been viewed as a less effective means to ensure heat and moisture to the inspired gas. More frequent endotracheal tube occlusions reported with HMEs probably explained this attitude. Opinions gradually changed when clinical studies indicated that (1) Endotracheal tube occlusion was no longer more frequent with HMEs than with HHs; (2) Long-term mechanical ventilation of many patients (including patients with chronic obstructive pulmonary disease) with HME was feasible and uneventful; (3) Cost of mechanical ventilation was dramatically reduced with the use of HME;and (4) Respiratory tubings were rapidly and heavily contaminated with HHs, a situation not encountered with HMEs. As a consequence, the debate surrounding HMEs and HHs has moved from humidification

issues to infection control and ventilator-associated pneumonia (VAP).[19] Despite the fact that in 1995, a pivotal study clearly showed similar rates of VAP in patients ventilated with an HME or with an HH,[20] efforts have been pursued in comparing HMEs and HHs in terms of VAP rates. These efforts have amounted to a number of studies, making it tantalizing to perform a meta-analysis (although the majority of the studies are negative). Two meta-analyses have already been published,[21,22] and the third one, by Dr. Siempos and colleagues,[23] these meta-analyses do not convey the same result! Hess et al[21] and Kola et al[22] reported a reduced risk of VAP with HMEs, whereas Dr. Siempos and colleagues found no effect. Both devices have their drawbacks: HMEs should be avoided during prolonged hypothermia[23] or severe hypercapnia with respiratory acidosis,[24] whereas worrisome shutdown of ventilators has been reported with HHs,[25,26] and these should be avoided in patients bearing multidrug-resistant bacteria in their respiratory tract or highly transmissible lung infection (tuberculosis, severe acute respiratory syndrome, avian flu).

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9 Chapter

Ventilator Graphics and Clinical Applications

Praveen Khilnani

Patients receiving respiratory support by mechanical ventilators need close monitoring in the pediatric intensive care unit, both for monitoring improvement or worsening in lung condition as well as for detecting and correcting potential problems leading to complications such as pneumothorax, hypoxemia, hypercarbia or rarely cardiac arrest.

Clinical monitoring of chest rise, breath sounds, color, oxygen saturation and the heart rate of the patient remain the best clinical parameters. In addition, end tidal CO_2 monitoring and arterial blood gas monitoring is required.

The popular ways to monitor patients in most ICU are shown in Figures 9.1A and B.

When checking the typical ventilator, the parameters examined are the Peak Inspiratory Pressure and the Exhaled Tidal Volume. The problem with these parameters is that we are only looking at two points in time (a zero mark and an end point).

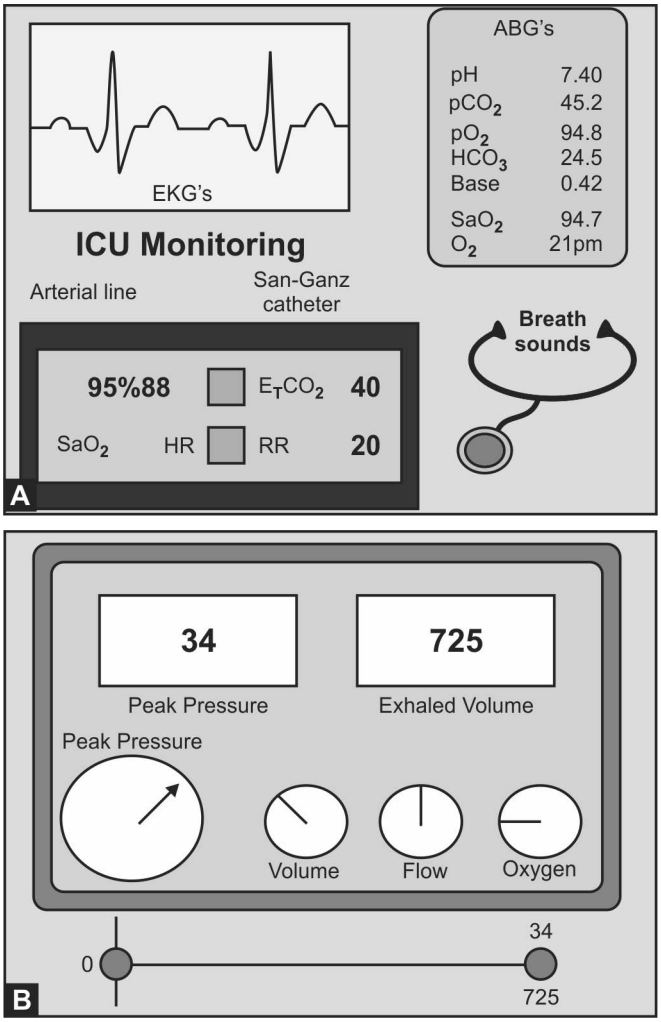
By looking only at these two parameters, one will not be able to tell if the patient has sufficient flow, hyperinflation, air trapping, secretions, appropriate PEEP levels, or airway obstruction.

Pulmonary monitoring with Graphics fills this gap. When using graphics, we see the entire breath from beginning to end. Ventilation decisions are made using thousands of points in time, not just two points in time. The graphics enable the clinician to see exactly what is going on in the lungs during mechanical ventilation.

The "art" of ventilation—evaluating clinically what the baby is doing and making changes in ventilation settings—is now being replaced by the "science" of ventilation–looking at data collected by respiratory function monitors and manipulating the ventilator accordingly.

With in line pulmonary mechanics monitor (now available on many ventilators) one can easily detect tube/circuit disconnection, tube obstruction, decreased lung compliance, brochospasm, patient ventilator dysynchrony, and auto-PEEP, and corrective measures can be instituted early to prevent potentially fatal complications.[1]

The use of noninvasive methods for the determination of the mechanical properties of the respiratory system in artificially ventilated patients has been advocated for the study of disease processes causing respiratory failure.



Figs 9.1A and B: Methods to monitor patients in ICU

Knowing the mechanical properties of the lung and the dynamics of lung-ventilator interaction should allow the optimum matching of mechanical support to the mechanical need.

Rosen et al[2] showed the effects of bedside pulmonary mechanics testing during infant mechanical ventilation in a retrospective analysis. In 251 neonates ventilated with the help of pulmonary mechanics testing, there was a significantly lower incidence of pneumothorax and intraventricular hemorrhage when compared to 217 neonates who were managed using similar ventilators without the help of pulmonary mechanics testing.

Fisher et al[3] have used pressure volume loops to identify and relieve lung distention during infant mechanical ventilation.

Although currently there are no studies available that directly show the effect of pulmonary function testing of ventilated patients on outcome in the pediatric intensive care unit, based on neonatal experience,[4-6] the application of pulmonary mechanics may have significant impact on morbidity and / or mortality of mechanically ventilated pediatric patients.

In western pediatric intensive care units and some units in India, monitoring pulmonary mechanics with in line measurement at the level of endotracheal tube, is a routine part of monitoring respiratory functions on all intubated pediatric patients with respiratory failure, in addition to monitoring of pulse oximetry, end tidal CO_2, arterial blood gases and FiO_2.[7-9]

Mechanical ventilation thus becomes much more individualized, using graphics. It allows to adjust ventilator's settings to fit each patient's needs. Ventilation can become much more dynamic, because a patient's needs may change several times during his stay on a ventilator.

There are three basic parts to respiratory function monitoring. There are "waves"(scalars), "loops" and indirect measurements (that is, volumes, compliance, and resistance which are calculated by changes in the measurements in pressure and flow). Given below are the definitions of the commonly used terminology when pulmonary mechanics are described.

Definitions

a. *Airway pressure* (P_{AW}): Peak airway pressure is pressure required to deliver a given tidal volume at a given rate. P_{AW} is affected by flow resistive and elastic properties of lung and chest wall.
   1. *Peak inspiratory pressure (PIP):* Pressure in the airways at the peak of the inspiratory pressure time waveform.
   2. *Plateau pressure (Pplat):* Pressure in the airways after peak inspiratory pressure when inspiratory pause / hold is in effect,and effectively resistance of the endotracheal tube / upper airways / trachea is overcome. This is considered to be alveolar pressure, used to measure static lung compliance.
   3. *Transpulmonary pressure* = P_{AW}-P_{ES} (pleural pressure). P_{AW} sampled at inlet of endotracheal tube represents proximal airway pressure.
   4. *Transairway pressure (PTA)* = (PIP-Pplat) Reflects pressure required to overcome airway resistance. It increases in situations such as bronchospasm, increased secretions, mucus plug.
   5. *Inadvertent (auto) PEEP:* Positive end expiratory pressure generated in the alveoli with air trapping during spontaneous or mechanical ventilation.
b. *Flow (V) is defined as Volume of gas flowing across a given point per unit time.* Flow is affected by air passage resistance, viscosity, humidity, temperature and mix of gas.
c. *Tidal Volume (Vt),* inspiratory and expiratory breath volume, is a function of gas flow and respiratory rate.
d. *Esophageal pressure* (Pes), is measured by balloon catheter placed in midesophagus. Pes is used as a reasonable approximation of pleural

pressure (PPI) in older children. In neonates with a distended chest wall, Pes may not correlate with Ppl.[3-5]

e. *Pressure Volume Curve:* Airway pressure is plotted against tidal volume.
f. *Flow Volume loop:* Inspiratory and expiratory flow is plotted against volume.
g. *Compliance (C)* is the measure of stiffness or distensibility (L / cm). Dynamic compliance (Cdyn) is tidal volume divided by total change in pressure required to deliver that volume. It is dependent on elastic (elastance and volume) as well as flow resistive (resistance and flow) properties of the lungs.
h. *Resistance (R):* Pressure divided by flow (cm / L / sec).
i. *Time Constant (TC):* Compliance X-resistance (sec). Time required to fill / empty an alveolus.
   - One Time Constant fills it 63%
   - Two Time Constants fill it 87%
   - Three Time Constants fill it to 95%
j. *Work of Breathing (WOB):* Area under the pressure volume curve is equal to the work of breathing. Increased resistance increases the work of breathing.[10]

TECHNIQUE OF RESPIRATORY MECHANICS MONITORING[11-15]

In a mechanically ventilated child, flow / pressure transducer connected at the endotracheal tube connection with the ventilator circuit is an essential component of respiratory mechanics monitoring. Airway pressure (P_{AW}), as well as flow can be accurately measured using this transducer. For measurements of compliance, resistance and time constant, an occlusion valve may be added to the ventilator circuit enabling pressure and volume measurements in addition to flow measurement.

An esophageal balloon catheter placed in mid-esophagus connected to the pulmonary function monitor measures Pes, which, in the absence of chest wall distortion, is considered in close approximation with pleural pressure (Ppl). Data from the transducer and esophageal balloon are processed by computer of the pulmonary function monitor and resulting pulmonary function parameters, e.g. *compliance, resistance, mean airway pressure and time constants can be printed.* Flow volume loops may also be obtained. The recorder display produces tracings of changes in airway pressure, esophageal pressure, airflow and tidal volume for each breath. Computer-assisted breath-to-breath studies can also be accomplished.

The flow transducer in line near the endotracheal tube measures two key variables:

1. Airway pressure (P_{AW})
2. Flow (V)

The addition of the occlusion valve to the circuit enables measurement of:

- Airway pressure (P_{AW})
- Compliance (Crs)
- Respiratory resistance (Rrs)
- Flow (V)

- Total resistance (RTS)
- Expiratory time constant.

The addition of the esophageal balloon catheter with tip placed in midesophagus enables measurement of pleural pressure in children and adults. In neonates, distortion of chest wall may affect the accuracy of:

- Esophageal pressure measurement.[16-18]
- Calculated parameters
- RR (Respiratory rate)
- PIP (Peak inspiratory pressure)
- PEEP (Positive end expiratory pressure)
- VE (Minute ventilation)
- Mean airway pressure (MAP)
- Peak inspiratory flow rate (PIFR) and expiratory flow rate (PEFR)
- Inspired and expired tidal volume
- Inspiratory and expiratory time.

Ventilator Waveforms

Currently all new generation mechanical ventilators have incorporated a graphic display of ventilatory waveforms.[19-21] These waveforms have significant utility in managing patients on mechanical ventilators. A clinician at the bedside can obtain valuable information from the graphics. The primary benefit of ventilator waveforms is detection of any abnormality and taking corrective action.

Although relatively new, graphics have slowly gained popularity among clinicians in pulmonary medicine, these graphics illustrate theoretical concepts associated with pulmonary mechanics. In ventilator graphics, researchers in pulmonary medicine have found a reliable tool to provide justification for their findings.[22-24] Clinicians are expected to use these waveforms to improve patient management on mechanical ventilation.

TYPES OF WAVEFORMS[25]

There are two types of ventilator waveforms: **Scalars and Loops**.

Scalars are tracings of three parameters: **Pressure, Volume and Flow against time**.

These waveforms display patterns that have clinical significance.

Loops plot two parameters against each other:

Pressure vs Volume and, **Flow vs Volume**.

Typical patterns of these loops are very useful in patient management.

Scalars

a. Flow vs Time (type of flow pattern)

Most ventilators allow the clinician to select a flow pattern that is most suitable for the patient (Fig. 9.2). Typically four types of flow patterns are available:

1. Square flow

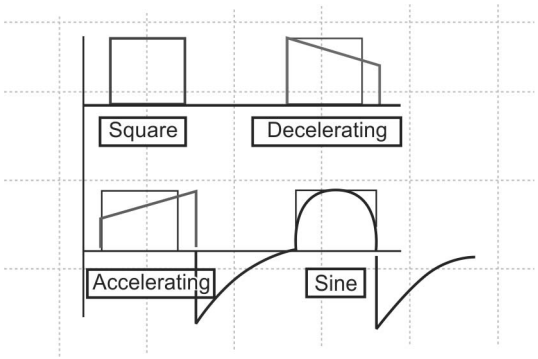


Fig. 9.2: Flow patterns

2. Descending ramp or decelerating flow
3. Ascending ramp or accelerating flow
4. Sine wave flow.

Observe that in each flow pattern illustrated on this frame the maximum flow rate is the same while Ti (inspiratory time)varies. However, if using a time-cycled ventilator, the Ti remains constant and the flow varies to accomplish the preset VT.

b. Pressure vs Time

Clinically very important waveform.

Components of Pressure-time curve.

Although dynamic lung mechanics can be observed from a Pressure vs Time curve, the addition of an inspiratory pause or inflation hold provides information to calculate static mechanics.

Plateau pressure (Pplat) or alveolar pressure is detected upon activation of an Inflation Hold or Inspiratory Pause control. The exhalation valve is kept in a closed position and the volume is held in the lungs. For clinical purposes, the plateau pressure is the same as the alveolar pressure. This measurement provides a means of measuring static lung compliance.

Transairway pressure (PTA = PIP – Pplat) reflects the pressure required to overcome airway resistance. Bronchospasm, airway secretions, and other types of airway obstructions are verified from an increase in the transairway pressure (PIP-Pplat) (Fig. 9.3).

With inflation hold, the clinician can determine the pressure required to overcome recoiling force (lung compliance). We can calculate static lung compliance by dividing the volume in the lung by the plateau pressure minus PEEP, if present.

$$Cs = \frac{VT}{Pplat - PEEP}$$

Waveforms

Identify pressure and flow waveforms of volume controlled ventilation.

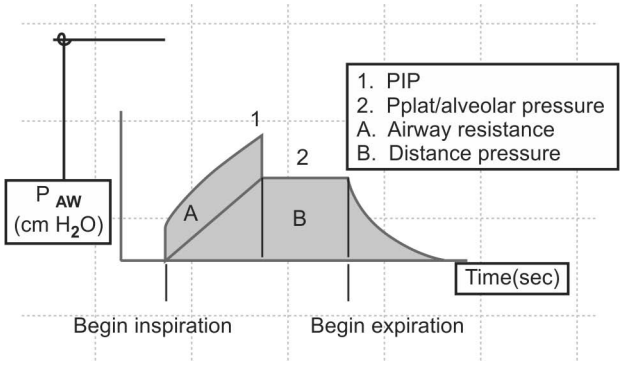


Fig. 9.3: Components of inflation pressure

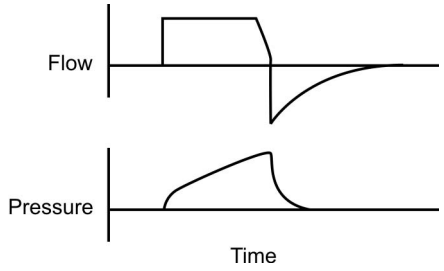


Fig. 9.4: Volume control—rectangular flow waveform

Rectangular Flow Waveform (Square wave): Features: Highest Peak Pressure, Lowest Mean Airway Pressure (Fig. 9.4.)

Descending Ramp Flow Waveform: Features: Lowest Peak Pressure, Highest Mean Airway Pressure (Fig. 9.5).

Sine Flow Waveform: Features:Peak pressure less than rectangular waveform and higher than descending. Mean Airway Pressure is higher than

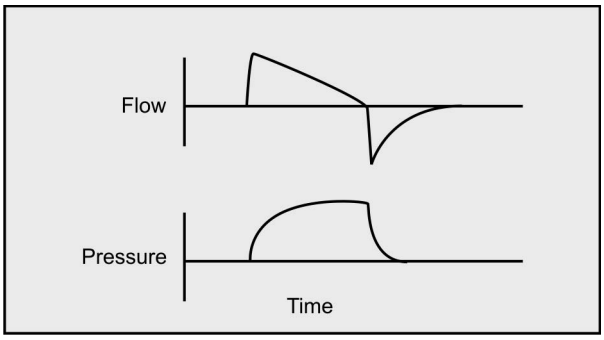


Fig. 9.5: Volume control—descending ramp flow waveform

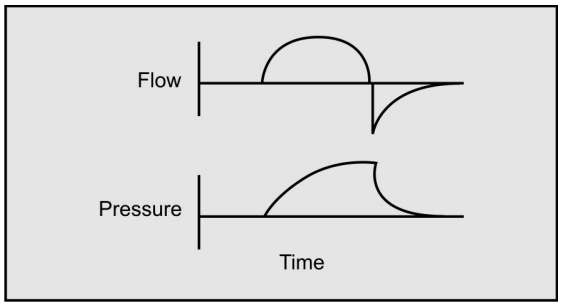


Fig. 9.6: Volume control—Sine flow waveform

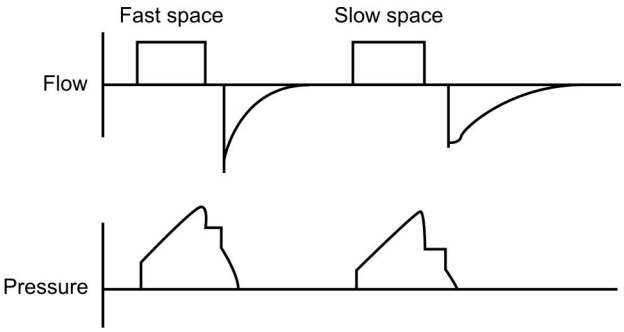


Fig. 9.7: Volume Control—rectangle flow waveform

rectangular waveform but lower than descending (Fig. 9.6). In a normal lung tissue based on the airway resistance and compliance of smaller alveolar units, there are fast alveolar units (Fast spaces), with low resistance, and normal or low compliance and slow alveolar units (Slow spaces) with high resistance and normal or high compliance.

Rectangular Flow Waveforms Comparing Fast and Slow Space Ventilation: Inspiratory flow wave remains constant. Expiratory flow takes longer to return to baseline with slow space. Plateau pressures are greater with fast space. The peak minus plateau pressure difference is greater in slow space due to the increased airway resistance and normal or increased compliance (Fig. 9.7).

Ramp Flow Waveforms Comparing Fast and Slow Space Ventilation: Changing to a ramp flow waveform lengthens inspiration and may cause air-trapping in slow space lung units. Expiratory flow takes longer to return to baseline during slow space ventilation. Peak and plateau pressures essentially equal each other in a ramp waveform since inspiratory flow has dropped to zero at end inspiration. Airway pressures are higher in fast space ventilation. The increase in airway pressure from high airway resistance in slow space ventilation is minimized with a ramp flow waveform (Fig. 9.8).

c. Volume vs Time

Provides information on volume delivered to the patient. Components of a Volume vs Time waveform. Information obtained from a Volume vs Time scalar graph includes a visual representation of (Fig. 9.9):

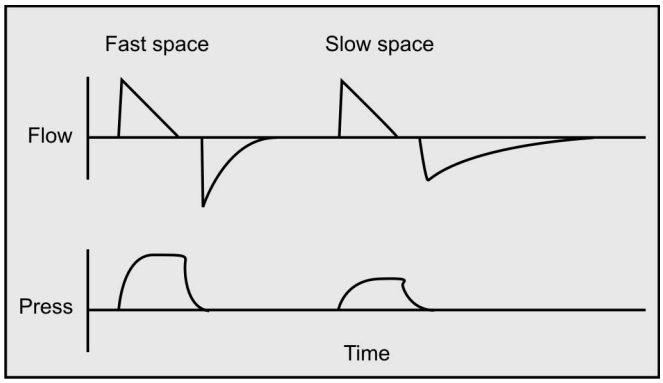


Fig. 9.8: Volume control—Rectangle ramp flow waveform

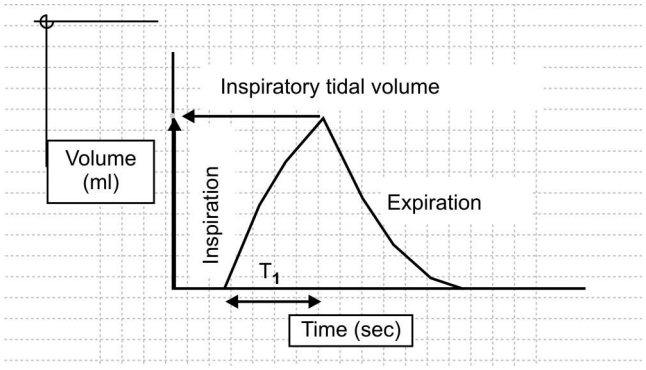


Fig. 9.9: Volume vs Time scalar

- Inspiratory Tidal Volume
- Inspiratory Phase
- Expiratory Phase
- Inspiratory Time.

Certain conditions may be easier to detect viewing volume waveforms. The first graphic shows flow/time and volume/time waveforms of a volume controlled breath during normal function. The second graphic shows the same breath with a pause added (Figs 9.10 to 9.13).

The next graphic is an example of what a leak in the circuit would look like in a volume waveform. The last set shows a volume waveform during a patient disconnection.

Pressure waveforms can be used to adjust Flow-by. In Flow-by, the patient's inspiratory effort creates a drop in flow, rather than a drop in pressure, to trigger a breath. If the flow sensitivity and base flow are adjusted properly, there should be little, if any, drop in pressure when the patient triggers a breath.

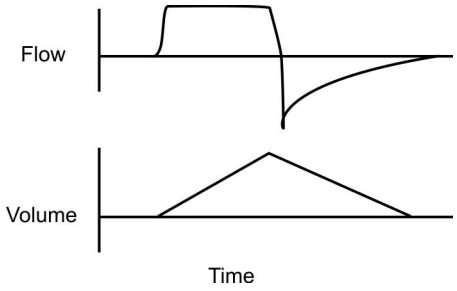


Fig. 9.10: Volume control—rectangular flow waveform

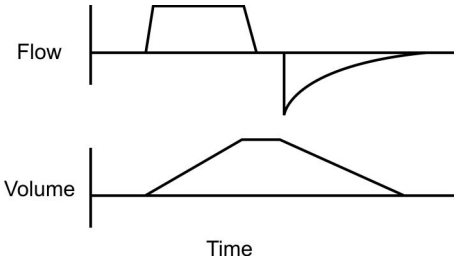


Fig. 9.11: Volume control—rectangular flow waveform with inspiratory phase

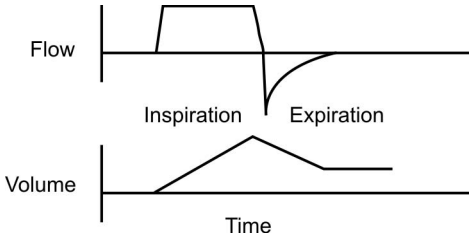


Fig. 9.12: Volume control—rectangular flow waveform with a leak

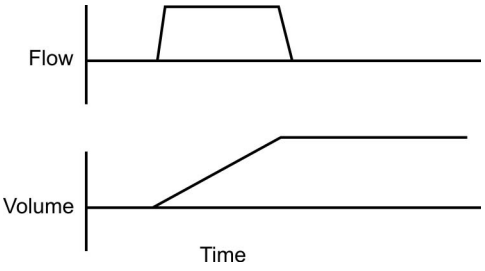


Fig. 9.13: Volume control—rectangular flow waveform during a patient disconnection

Loops

Pressure-Volume Loop

Clinically very important tracing, components of a P-V Loop are: A Pressure-Volume loop traces changes in pressures and corresponding changes in volume. Inspiration begins from the FRC level and terminates when the preset parameter (volume or pressure) is achieved. The tracing continues during expiration and returns to FRC at end of exhalation. PIP and delivered tidal volume are readily obtained from the Pressure-Volume loop.

Flow-Volume Loop

Detects abnormalities in flows associated with obstruction. Components of a Flow-Volume Loop (Figs 9.14 to 9.16) are: There is no set convention in assigning the inspiratory and expiratory quadrants on a Flow-Volume loop. Some ventilators produce flow-volume loop with inspiration on the upper quadrant and expiration on the lower quadrant. Other ventilators plot inspiration on the lower side of the volume axis and expiration on the upper side (Figs 9.17A and B).

A flow-volume loop provides the following information:

1. PIFR (Peak inspiratory flow rate).

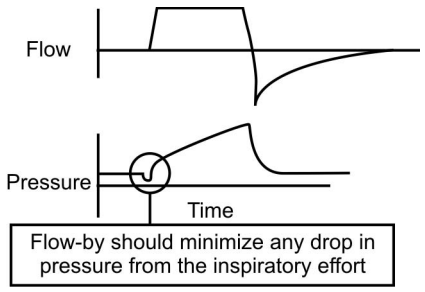


Fig. 9.14: Volume control—rectangular flow waveform with flow by and PEEP

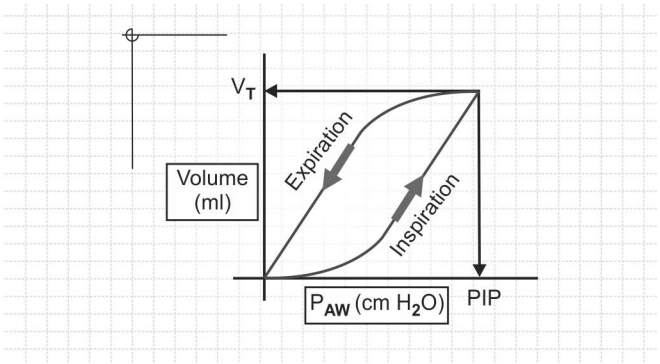


Fig. 9.15: Pressure-volume loop

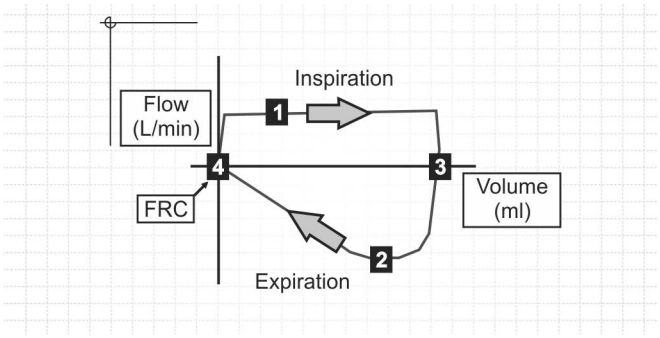


Fig. 9.16: Flow-volume loop

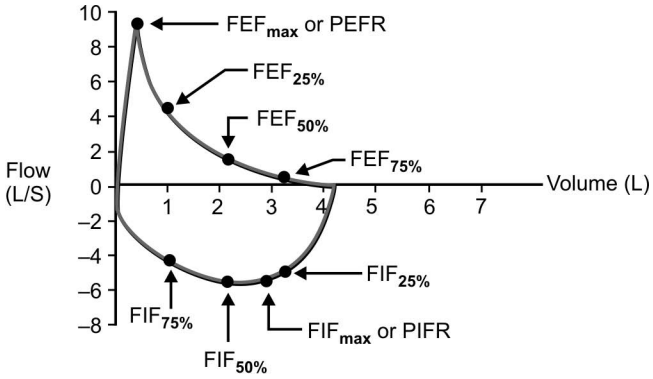


Fig. 9.17A: Flow volume loop on spirometry: Note the various points on the loop (FEF—forced expiratory flow; FIF—forced inspiratory flow; PIFR—peak inspiratory flow rate; PEFR—peak expiratory flow rate)

2. PEFR (Peak expiratory flow rate).
3. Tidal Volume.
4. End of Expiration and Beginning of Inspiration.

Clinical application of flow Volume Loop:

1. *Fixed upper airway obstruction:* Tracheal stenosis, undersized endotracheal tube, kinked or plugged endotracheal tube can be detected because both expiratory and inspiratory parts of the flow volume loop look flat, i.e. reduced flow during inspiration as well as expiration.
2. *Variable extrathoracic obstruction:* Flat peak flow during inspiration.
3. *Variable intrathoracic obstruction:* Flat peak flow during expiration.
4. *Restrictive lung disease:* Decreased flow and tidal volume during inspiration.
5. *Asthma:* Decreased peak flow in maximal expiratory flow volume curve.

Flow / volume loops help in evaluating whether airway obstruction lessens after bronchodilator therapy. Improvement would result in a higher peak expiratory flow (top half). Keep in mind that these breaths are not

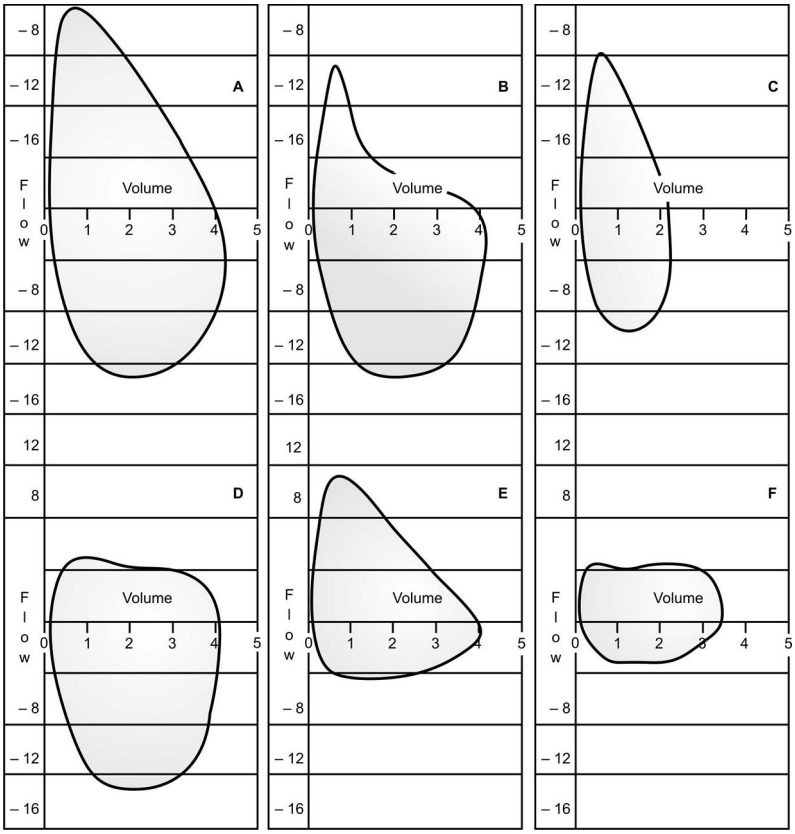


Fig. 9.17B: Characteristic flow-volume loops. A: Normal flow-volume loop; B: Patient with symptomatic severe asthma/cystic fibrosis; C: Restrictive lung disease, child with neuromuscular disease; D: Child with severe tracheomalacia (intrathoracic obstruction); E: Inspiratory flow limitation in a patient with vocal cord paralysis; F: Fixed obstruction in a patient with subglottic stenosis

forced exhalations. If there are higher expiratory flows from a reduction in airway obstruction, there would be less of a scooped appearance during mid to end exhalation (Fig. 9.18).

ABNORMAL WAVEFORMS

Auto-PEEP or Air Trapping

Normally, expiratory flow returns to the baseline prior to the next breath. In the event that the expiratory flow does not return to the zero line and the subsequent inspiration begins below the baseline, auto-PEEP or air trapping is present (Fig. 9.19).

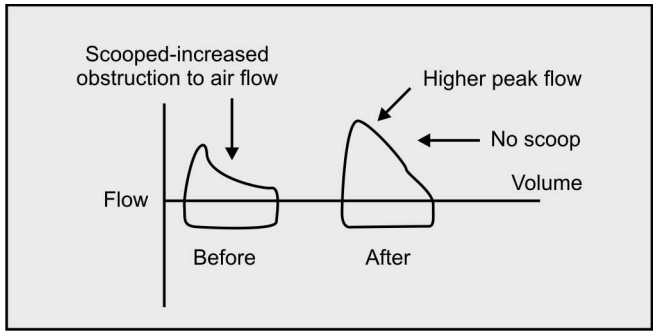


Fig. 9.18: FVL indicates positive bronchodilator response

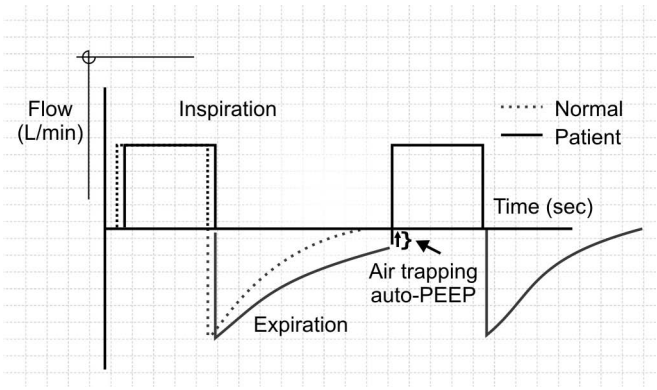


Fig. 9.19: Air trapping

The presence of auto-PEEP or air trapping may result from:

a. Inadequate expiratory time.
b. Too high a respiratory rate.
c. Long Inspiratory Time.
d. Prolonged exhalation due to bronchoconstriction.

Even though auto-PEEP is best detected from the flow-time waveform, its magnitude is not directly measured from the flow-time scalar. A higher inspiratory flow rate (in volume-cycled ventilators) or short Ti (in time-cycled ventilators) allows for a longer expiratory time and may eliminate auto-PEEP.

Increased Airway Resistance (Raw)

PIP vs Pplat

Changes in the pressure vs time curve have notable clinical significance. Figure 9.20 illustrates four common clinical situations:

1. *Normal curve:* Indicates PIP, Pplat, PTA, and Ti.
2. *High raw:* A significant increase in the PTA is associated with increase in airway resistance.

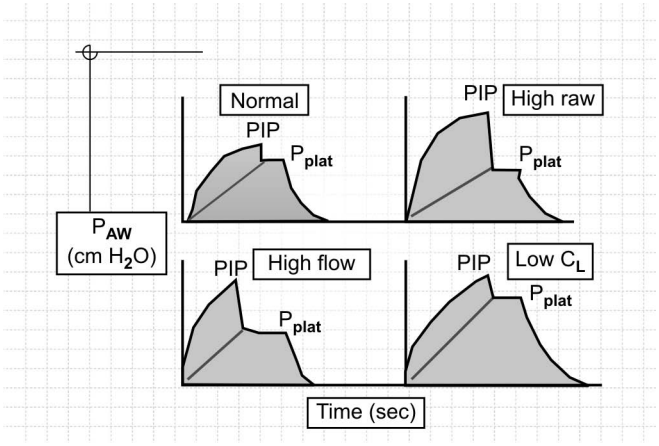


Fig. 9.20: PIP vs Pplat

3. *High flow:* Notice that the inspiratory time is shorter than normal, indicating a higher inspiratory gas flow rate.
4. *Decreased lung Compliance:* An increase in the plateau pressure and a corresponding increase in the PIP is consistent with decreased lung compliance.

Decreased Lung Compliance during Volume Ventilation

A shift of the curve to the right of a Pressure-Volume loop indicates decreased lung compliance. A shift to the left is associated with an increased compliance. Observe the pressure required to deliver the same tidal volume in the three graphs. Higher pressure is required to deliver same tidal volume in a low compliance (shift to the right)situation (Fig. 9.21).

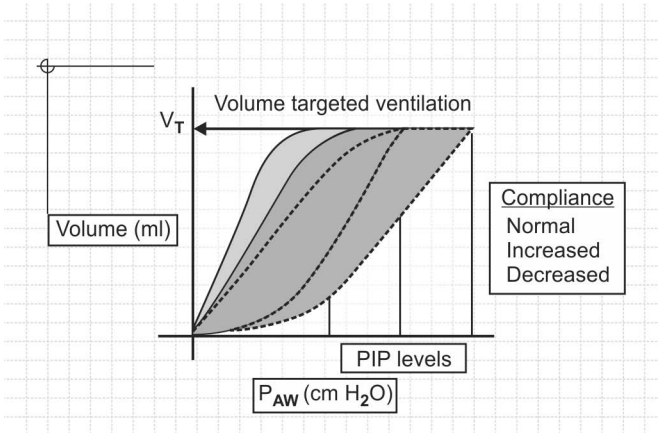


Fig. 9.21: Lung compliance changes in the P-V Loop

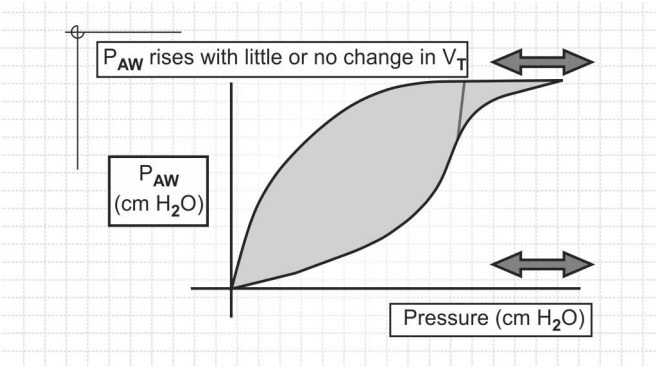


Fig. 9.22: Overdistention

Alveolar Overdistention

Alveolar distention is a common observation made during ventilation of patients with ARDS on a volume-targeted mode. Alveolar overdistention is detrimental to patients. The classic sign, known as "Beak Effect" or "Duckbill" shows an increase in airway pressure without any appreciable increase in volume. In this situation it is desirable to switch to pressure targeted ventilation at appropriate safe pressure level, or a reduction in Vt (Fig. 9.22).

Modes of Ventilation

Modes of ventilation are generally volume control or pressure control, and either of these modes will give clinicians the option of augmenting a spontaneous breath between the mandatory breaths by using pressure support. Mandatory breaths occur when either the patient or the machine triggers the breath to start and the breath itself is cycled into expiration by the machine. Spontaneous breaths occur when the patient initiates the breath and cycles the breath into expiration. Pressure-support ventilation augments the spontaneous breaths by adding flow (in a decelerating pattern) to reach a preset inspiratory pressure; this results in an increased tidal volume. Pressure support is available only in those modes that allow for spontaneous breaths. Positive end-expiratory pressure (PEEP) is one other common addition to volume-control and pressure-control modes.

Scalar Waveforms of Pressure and Volume Controlled Ventilation

Figure 9.23 shows a side-by-side comparison of the pressure-time, volume-time, and flow-time waveforms for volume-control versus pressure-control ventilation over four breaths.

Both examples show that the ventilator settings include 10 cm H_2O of PEEP, shown by the baseline tracing at +10 on the pressure-time waveforms.

On both tracings, the first and last breaths are mandatory, the first breath is time triggered, and the last three breaths are patient triggered (as seen in the triggering deflection on the pressure-time waveform). Pressure

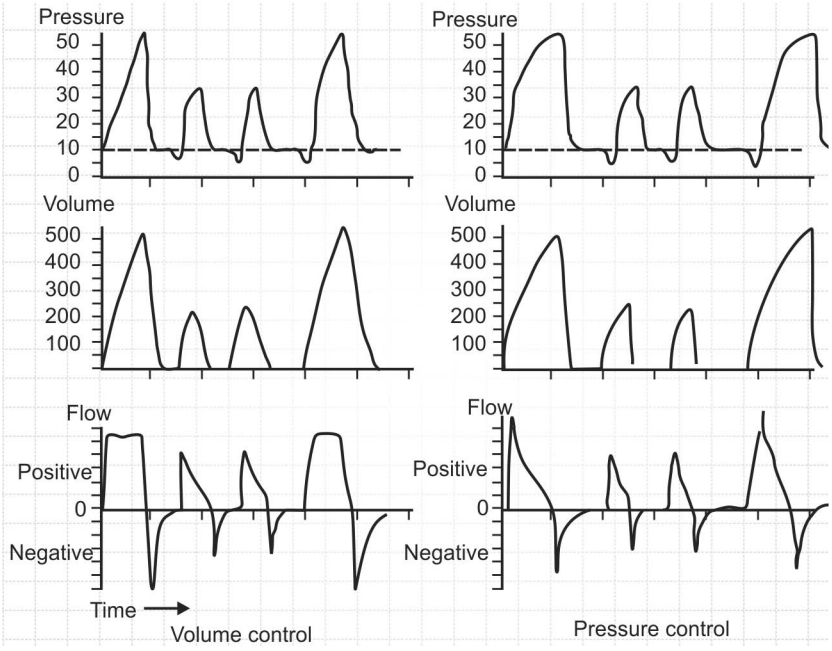


Fig. 9.23: Volume control vs pressure control ventilation over four breaths

support of 20 cm H_2O is being delivered during the two spontaneous (second and third) breaths.

Scalar Waveforms during Common Modes of Ventilation in Volume-Targeted Ventilation

a. Controlled.
b. Assist controlled.
c. SIMV (synchronized intermittent mandatory ventilation).
d. SIMV with pressure support.

Note: A square flow pattern will be used to identify the inspiratory phase of the mechanical breaths in the Flow *vs* Time curve.

Controlled Mode

In a controlled mode, the ventilator provides the entire breathing. The ventilator exclusively performs the work of breathing. The ventilator initiates inspiration when a preset time elapses (Time- triggered). It terminates inspiration when the preset tidal volume is delivered (Fig. 9.24).

Assisted Mode

An assisted mode is identical to a controlled mode except that the Pressure vs Time curve shows a negative deflection just prior to the mechanical breath. This negative deflection indicates patient triggering (Fig. 9.25).

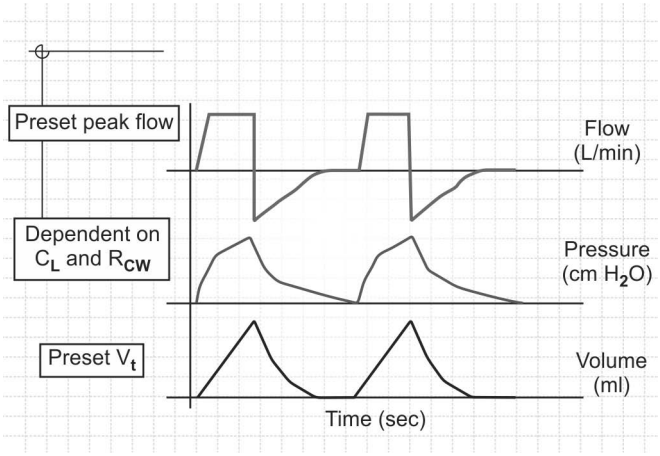


Fig. 9.24: Controlled mode (Volume-targeted ventilation)

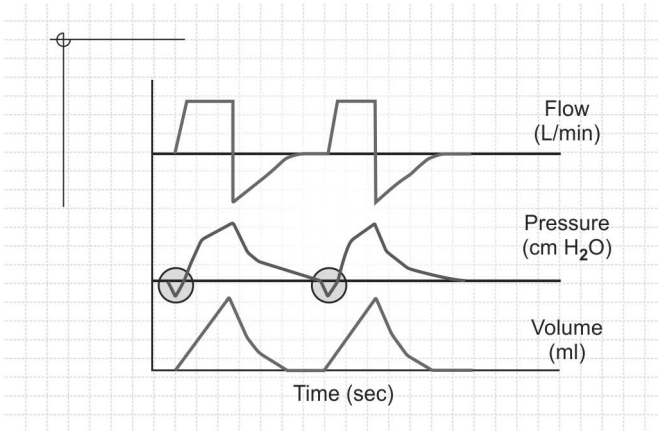


Fig. 9.25: Assisted mode (Volume-targeted ventilation)

SIMV (Synchronized Intermittent Mandatory Ventilation)

This is the most common mode used in the clinical settings. It is primarily used to provide partial mechanical support. The patient's spontaneous breathing is supported with periodic assisted mechanical breaths (Fig. 9.26).

SIMV with Pressure Support (PS)

It is recommended that PS be added to SIMV to provide augmentation of unsupported spontaneous breath through the endotracheal tube.

Each breath is a patient triggered breath. Volume delivered during mechanical breaths is preset. However, the volume delivered by the Pressure Supported breath is dependent on the level of pressure support, patient's lung compliance, airway resistance, and patient's inspiratory effort (Fig. 9.27).

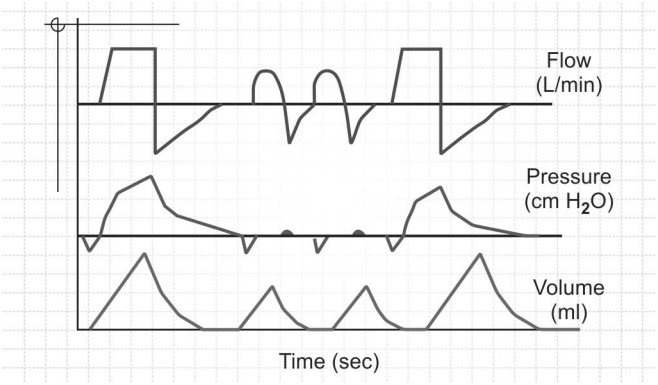


Fig. 9.26: SIMV—volume-targeted ventilation

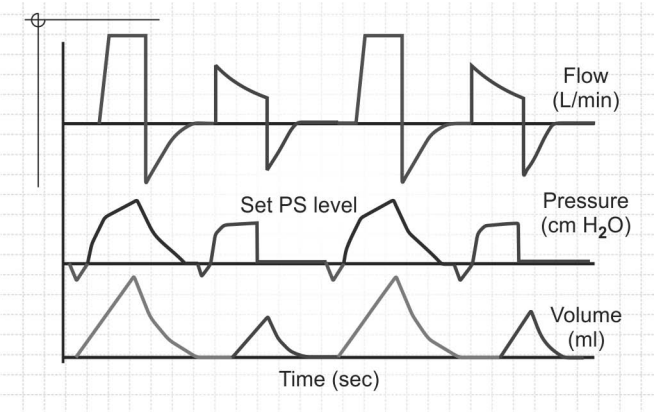


Fig. 9.27: SIMV + PS—volume-targeted ventilation

Clinical Applications and Significance

Clinical applications and significance of respiratory mechanics monitoring in mechanically ventilated patient can be following:

a. Detect lung overdistention / prevent pneumothorax.
b. Identify patient ventilator dysynchrony.
c. Track rapid changes in tidal volume and compliance.
d. Detect endotracheal tube obstruction, right mainstem intubation, bronchospasms and pneumothorax.
e. Assess efficacy of bronchodilator therapy.
f. Monitor tidal volume, minute ventilation for spontaneous as well as mechanical breaths.
g. Other potential uses:
    1. Effectiveness of pressure support ventilation.
    2. Assessment work of breathing.
    3. Measure muscle strength by measuring maximal inspiration and expiratory pressures.

Conclusions

Graphics can aid clinicians in deciding which ventilator mode is most appropriate, or in fine-tuning the settings for a given mode in order to achieve the best combination for the patient. As the clinicians become more familiar with ventilator graphics, the more unusual and difficult waveforms and loops will be easier to understand and correct. Patient comfort and the effectiveness of ventilation are two important aspects of care that can be improved using the information provided by the graphics .Ventilator graphics constitute a valuable tool, and a thorough understanding of the associated patterns, problems, and corrections will help to provide high-quality, effective care.

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FURTHER READING

1. "Essentials of Ventilator Graphics" an interactive CD created by Dr Ruben Restrepo and Vijay Deshpande (www.respiratorybooks.com).

10 Chapter

Ventilation for Acute Respiratory Distress Syndrome (ARDS)

Shipra Gulati, Praveen Khilnani

INTRODUCTION

Acute lung injury (ALI) and its more severe form, acute respiratory distress syndrome (ARDS),are devastating disorders of overwhelming pulmonary inflammation leading to hypoxemia and respiratory failure.

The American European Consensus Conference (AECC) ALI and ARDS criteria[1] are used most commonly to diagnose ALI and ARDS in adults and children, utilizing four clinical parameters: (a) acute onset; (b) severe arterial hypoxemia resistant to oxygen therapy alone (PaO_2/FIO_2 ratio < 200 torr (< 26.6 kPa) for ARDS and PaO_2/FIO_2ratio < 300 torr (< 40 kPa) for ALI); (c) diffuse pulmonary inflammation (bilateral infiltrates on chest radiograph); and (d) no evidence of left atrial hypertension.

EPIDEMIOLOGY OF ACUTE LUNG

Injury and ARDS in Children

The risk factors and pathophysiology of ALI/ARDS are similar in adults and children.[2] The most common trigger is infection,most commonly in the lower respiratory tract. ALI/ARDS occurs with less frequency in children than in adults. In King County Washington, the frequency of ALI is 16 per 100,000 person-years for those 15 through 19 years of age (mortality 24%).

Estimates from other countries on pediatric ALI occurrence range from 2.2 to 12 per 100,000 pediatric population.[3-5]

DIAGNOSING ACUTE LUNG INJURY

Clinical consensus criteria such as the AECC criteria, described above are the common method for diagnosing the syndrome. Despite its limitations, the AECC criteria do capture a population of children with prolonged duration of respiratory failure (average duration of mechanical ventilation of 10–16 days) and relatively high mortality (10–40% overall). The Murray Lung Injury Score is another clinical definition of ARDS that incorporates lung compliance and level ofpositive end-expiratory pressure on the ventilator along with PaO_2/FIO_2 ratio and degree of alveolar consolidation.[6] It has been used in a single center study of infant with viral lower

respiratory infection,[7] successfully identifying those with higher morbidity and mortality. This score may hold promise for distinguishing between ALI and bronchiolitis in young children.

Decreased duration of mechanical ventilation is an accepted measure of improved lung function resulting from decreased lung inflammation, even if overall mortality is only minimally altered by an intervention. Data on long-term outcomes in pediatric ALI/ARDS are lacking.

MANAGEMENT OF PEDIATRIC ALI AND ARDS

Untreated infection, necrosis of tissue, pancreatitis, and other persistent triggers of the inflammatory cascade will lead to unrelenting escalation of ARDS.[1] Identification of the ARDS trigger source and achievement of source control are essential to optimize clinical outcomes. Because sepsis is commonly the trigger of ALI, early antibiotic therapy is recommended in those suspected of being infected.[8]

Therapies for ALI/ARDS are targeted at decreasing mortality and morbidity, hastening recovery, and optimizing longterm cognitive and respiratory function. It is important to minimize profound hypoxia that leads to cell death and is damaging to the developing brain, and to minimize secondary damage to the injured lung and other organ systems that could prolong recovery.

RESPIRATORY SUPPORT IN CHILDREN WITH ALI AND ARDS (SEE CHAPTER 5)

The National Institutes of Health ARDS Clinical Trials Network (ARDSNet) published ventilator management protocol for a (http://www.ardsnet.org/) uses a PaO_2 target of 55 to 80 torr (SpO_2 target 88–95%). The effect of tolerating lower levels of oxygenation for prolonged periods on the developing brain is unknown; long-term follow-up studies in pediatric ALI/ARDS that evaluate neurologic function have not been performed.

Maintenance of a PaO_2 of 60 to 80 torr (or SpO_2 > 90%) is usually considered safe in children with ALI/ARDS; however there are no studies supporting the safety of this therapeutic target.

If achievement of a normal pH and normal $PaCO_2$ requires respiratory support strategies that are potentially damaging to the lung, lower pH and higher $PaCO_2$ levels should be tolerated.[9] It is believed that very high $PaCO_2$ levels are not damaging to the brain, but rigorous long-term outcome studies in children with ALI/ARDS have not been performed optimally, the target arterial pH levels in children with ALI/ARDS is the same as in adults (pH 7.30 to 7.45).[10]

Although, some children survive ALI/ ARDS requiring only supplemental FIO_2, most patients require assisted ventilatory support.[11] Infants and small children are at a disadvantage compared with larger children and adults due to smaller airways with increased airway resistance, less rigid chest walls, and lower functional residual capacity, all of which lead to a higher risk of respiratory failure and more rapid development of sustained hypoxia. A meta-analysis of the literature of noninvasive

positive-pressure ventilation use in adults with ARDS concluded that there is no proven effect on mortality or need for intubation, although population heterogeneity limited conclusions.[12] A randomized trial of use of noninvasive positive-pressure ventilation to prevent reintubation after failed extubation in a mixed population of critically ill adults concluded that noninvasive positive-pressure ventilation did not reduce the risk of reintubation or reduce mortality.[13] In children, a Cochrane Collaboration review concluded that there is a lack of well-designed, controlled experiments of noninvasive positive-pressure ventilation in children with acute hypoxemic respiratory failure.[15] Only one small before-after study in bronchiolitis[14] and a very small randomized trial in acute hypoxemic respiratory failure[16] have been published.

Heated high flow nasal cannula (HFNC) FIO_2 in infants and children with ALI/ARDS has been used increasingly in neonatal and pediatric intensive care units in which continuous positive airway pressure (CPAP) may have been instituted. Three neonatal studies reported delivery of unpredictable levels of CPAP with HFNC.[17-19] A randomized trial in neonates < 1250 g showed that CPAP delivered by HFNC failed to maintain extubation status compared with conventional CPAP.[20] The HFNC humidification levels can also promote bacterial overgrowth and require adherence to infection control protocols.[21]

ENDOTRACHEAL INTUBATION AND VENTILATION

Cuffed endotracheal tubes can be used safely in infants and young children,[22] and may be optimal to ensure adequate positive end-expiratory pressure delivery in the face of low pulmonary compliance. Although mechanical ventilatory support is life-saving, low lung compliance and high ventilatory pressures can lead to ventilator-induced lung injury from alveolar overdistention (volutrauma), repeated alveolar collapse and reexpansion (atelectrauma), and oxygen toxicity.[23] Reducing plateau pressure to < 30 cm H_2O by targeting tidal volumes to < 6 mL/kg with positive end-expiratory pressure (PEEP) decreased mortality in the ARDSNet trial in adults with ARDS.[10] There is much controversy over whether low tidal volumes, maintenance of plateau pressure < 31 cm H_2O, or both are necessary to improve outcomes in ALI/ARDS.[24,25] It has been speculated that reproduction of the pivotal ARDSNet tidal volume study would not be possible in children due to lack of clinical equipoise.[26] Results of studies with historical controls suggest that use of lower tidal volumes and higher positive end-expiratory pressure levels in pediatric ALI/ARDS have become more standard over time and may explain the improvement of outcomes reported over the past two decades.[26–28] One randomized trial of prone positioning in children with ALI/ARDS employed a modified ARDSNet low tidal volume ventilatory management protocol with an overall mortality rate of only 8%, the lowest reported till date.[29] In contrast, a recent observational study of 117 children with ALI/ARDS in Australia and New Zealand (overall mortality < 37%) showed that higher maximum and median tidal volumes were associated with reduced mortality.[3] For new practice of law and tidal volumes with PEEP titration appears to be

safe. PEEP levels of up to 15-20 cm H_2O have been used. Fluid therapy, inotropic support and use of chest tubes to treat pneumothorax should be anticipated due to use of high PEEP and cardiac vascular compromise.

Weaning

There have been no clinical trials evaluating methods of weaning from mechanical ventilation specifically in children with ALI / ARDS. In a heterogeneous group of children with respiratory failure from pulmonary and neurologic etiologies, including ALI / ARDS, there was no difference between physician driven weaning vs. either of two different pressure support-based weaning protocols.[30] Although, all children did not meet the extubation criteria before randomization, the duration of time in weaning was very brief (1.6–2 days) in all three study arms. There is no evidence to support a specific mechanical ventilatory weaning method for children with ALI / ARDS.[31] Studies have reported extubation failure rates of 10 to 20%, most commonly associated with upper airway swelling, in heterogeneous populations of children with respiratory failure.[31] Absence of an airleak around the endotracheal tube at 30 cm H_2O pressure, however, is not predictive of extubation failure in children.[32] A recent evidence-base review concluded that there are no extubation criteria for children with ALI / ARDS that are proven more accurate than expert clinical judgment.[31] The PALISI Network used three criteria: (a) minimal tidal volume of 5 ml / kg exhaled measured at the endotracheal tube; (b) a SpO_2 of > 95% on positive end-expiratory pressure < 5 cm H_2O and FIO_2 < 50%; and (c) a respiratory rate that was appropriate for age to test a heterogeneous group of children with respiratory failure that physicians believed needed to be weaned from mechanical ventilatory support.[30] Using these criteria led to an extubation failure rate of 15%. Similar outcomes were found, using a T piece trial.[33] A significant proportion of children with ALI / ARDS being evaluated for weaning may actually tolerate extubation, if tested.[30,31] Bronchodilators are used commonly in children with ALI / ARDS but there are no clinical trials in children with ALI / ARDS. Asthma is the most common comorbid condition in mechanically ventilated children.[34] Bronchodilators should be considered only in children with evidence of bronchospasm.

Therapies that Improve Oxygenation but not Clinically Important Outcomes

Similar to studies in adult patients,[35] a recent randomized, controlled study performed by the PALISI Network in children with ALI showed no significant benefit of prone positioning (20 hrs / day for 7 days) on VFDs despite improved oxygenation. Inhaled nitric oxide is a potent pulmonary vasodilator and doses as low as 1 ppm can improve oxygenation in ALI / ARDS.[36] A meta-analysis of multiple studies showed that inhaled nitric oxide improved oxygenation without improving overall clinical outcomes in children and adults with ALI / ARDS.[37] Aerosolized prostacyclin also improved oxygenation in 8 / 14 children with ALI / ARDS.[38]

Prolonged duration of mechanical ventilation puts children with ALI/ARDS at risk for developing nosocomial infections, including ventilator-associated pneumonia (VAP). Selective decontamination of the digestive tract has been shown to decrease mortality in adults requiring prolonged mechanical ventilation presumably by decreasing development of VAP.[39,40] There are some reports suggesting a rationale for use of selective decontamination of the digestive tract in critically ill mechanically ventilated children.[41] There is no evidence that selective decontamination of the digestive tract improves clinically important outcomes in children with ALI/ARDS.

RESCUE THERAPIES FOR CHILDREN WITH ALI/ARDS

High-frequency oscillatory ventilation uses high-frequency very-low tidal volumes and laminar air flow to protect the lung. One crossover trial comparing rescue high-frequency oscillatory ventilation with conventional mechanical ventilation in pediatric ALI/ARDS[42] showed that high-frequency oscillatory ventilation was associated with higher mean airway pressures, improved oxygenation, and a reduced need for supplemental oxygen at 30 days. Use of high-frequency oscillatory ventilation has become ingrained in pediatric practice and is used frequently in children with ARDS,[34] despite lack of evidence to support it. Extracorporeal membrane oxygenation has been used as a rescue therapy for over two decades in children with ALI/ARDS, with reported survival rates of > 50%.[43] An attempt at a randomized trial of extracorporeal membrane oxygenation for ARDS in children failed due to a drop in baseline mortality. This was hypothesized to be associated with increased use of lung protective ventilation strategies.[44] Given the need for anticoagulation and the increased risk of bleeding in children who receive extracorporeal membrane oxygenation, its use should be limited to those patients in whom conventional therapies have failed.

POTENTIALLY PROMISING THERAPIES FOR CHILDREN WITH ALI/ARDS

Trials of endotracheal surfactant in adult patients with ALI/ARDS have been negative,[45] with speculation that efficacy may be higher in patients with direct lung injury.[46] A PALISI Network randomized trial of Calfactant in children with ALI/ARDS showed improved oxygenation and decreased mortality but no improvements in the course of respiratory failure (ventilator days, hospital, or intensive care unit length of stay).[47] A meta-analysis of six trials of surfactant therapy in children with acute respiratory failure including bronchiolitis and ALI showed decreased mortality, increased VFDs, and decreased duration of mechanical ventilation.[48] Delivery of surfactant to children with ALI/ARDS is not without risks, including hypotension, hypoxia, and barotrauma,[47] and must be done by skilled surfactant administrators. Surfactant is expensive but may be cost effective in ALI treatment.[49] There are two ongoing clinical trials across

the PALISI Network, evaluating the effect of endotracheal surfactant (Calfactant and Lucinactant) in children with ALI.

In adults with ARDS, a recent meta-analysis of corticosteroids in ALI / ARDS[50] led to the following conclusions: (a) preventive steroids (four trials) might increase the risk of adult patients developing ARDS and may increase mortality in those who develop ARDS; and (b) steroids in patients with ARDS may reduce mortality and was associated with an increase in VFDs without increasing the risk of infection. There have been no studies of corticosteroids for treatment of ALI / ARDS in children.

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11 Chapter

Mechanical Ventilation in Acute Asthma

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INTRODUCTION

Mechanical ventilation in asthma represents a big challenge to the intensivists, with mortality rates in patients requiring ventilation approaching as high as 10%.[1] Despite the comprehensive pharmacological and supportive treatment available today to treat asthma exacerbations, there continues to be an important proportion of patients who require ventilatory support. Hence, familiarity with the condition of the critically ill patient and an in-depth understanding of the pathophysiology of asthma are essential for effective management.

The onset of acute asthma symptoms ranges from hours to weeks. Type I acute asthma, also known as slow-onset asthma, often presents as a gradual deterioration of the clinical scenario, which is superimposed on a background of chronic and poorly controlled asthma. Type II acute asthma or rapid-onset asthma, tends to be more dangerous and frequently presents with sudden narrowing of the airways.

Careful and repeat assessment of patients with severe exacerbations is mandatory. Patients who deteriorate despite aggressive treatment should be intubated. The exact time to intubate is based mainly on clinical judgment, but it should not be delayed once it is deemed necessary.

CRITERIA FOR INTUBATION

Clinical: Decision to intubate a patient is largely based on clinical grounds. Indications to intubate in acute asthma include: (a) Cardiac arrest, (b) Respiratory arrest or profound bradypnea, (c) Physical exhaustion, and (d) Altered sensorium, such as lethargy or agitation, interfering with oxygen delivery or anti-asthma therapy.

Respiratory acidosis: In the past, respiratory acidosis or an increasing $PaCO_2$ was considered an indication for intubation; however, a systematic review of the literature by Leatherman determined that intubation might not be necessary for a successful outcome in most asthmatic patients with hypercarbia.[2] Intubation is indicated with a progressively increasing $PaCO_2$ that is unresponsive to therapy and possibly associated with a change in mental status; however, a high $PaCO_2$ alone might not be an indication for intubation, provided the patient has no change in mental status and does

not appear to be exhausted.[3] Intubation should be performed in a controlled setting by a physician with extensive experience in intubation and airway management.

INTUBATION TECHNIQUE

Once the decision to intubate has been made, the goal is to take rapid and complete control of the patient's cardiopulmonary status. There are 4 methods of intubation, including awake nasotracheal intubation, awake orotracheal intubation, orotracheal intubation with sedation, or orotracheal intubation with sedation and neuromuscular blocks. The oral route for intubation appears to offer advantages over the nasal route. It allows a larger endotracheal tube that offers less resistance and greater airway clearance possibilities. The nasal route may be preferred in the conscious, breathless, obese patient who may be difficult to ventilate with a bag-valve mask.[4]

Sedation can make intubation easier to achieve. Intubation with a rapid sequence of sedation and muscle paralysis is preferred, although some advocate awake intubation because of concern for the potential for apnea with sedation.[5]

SEDATION DURING INTUBATION AND VENTILATION

Effective sedation is essential during intubation and to allow synchrony between the patient and the ventilator.[6] Also, sedation improves patient comfort, decreases oxygen consumption and carbon dioxide production, decreases the risk of barotrauma, and facilitates procedures. There is no standard sedation protocol for the asthmatic patient.

Benzodiazepines: Midazolam can be administered at a dose of 0.1 mg / kg IV and may be repeated until the patient allows positioning and airways inspection. Benzodiazepines have minimal adverse effects but are usually not sufficient to suppress respiratory drive.

Ketamine: It is an intravenous general anesthetic with sedative, analgesic, anesthetic, and bronchodilating properties that appears useful in the emergency intubation for asthma.[7] During intubation, the intravenous administration of 1–2 mg ketamine / kg at a rate of 0.5 mg / kg / min results in 10–15 minutes of general anesthesia without significant respiratory depression. Bronchodilation appears within minutes after intravenous administration and lasts 20–30 minutes after cessation. Ketamine is contra-indicated in hypertension and cardiovascular disease due to its sympatho-mimetic effects. Other side effects of ketamine include increased respiratory secretions, altered mood, delirium, laryngospasm, and aspiration. Furthermore, since ketamine is metabolized by the liver to norketamine, which also has anesthetic properties and a half-life of about 120 minutes, drug accumulation may occur and lead to prolonged side effects.

Propofol: It is an excellent sedating agent since it has a rapid onset and a rapid resolution of its action.[8] In addition, it has bronchodilating properties

and it may avoid the need for paralytic agents. Propofol is administered intravenously during the peri-intubation period at a dose of 1-2 mg / kg. It causes hypotension which should be managed with fluid boluses and vasopressors. Prolonged propofol administration may be associated with generalized seizures, increase in carbon dioxide production, refractory metabolic acidosis and hypertriglyceridemia.

Opioids: These are potent suppressors of respiratory drive, however are not recommended for sedation in asthmatics because of their potential to induce bronchoconstriction and hypotension through direct vasodilatation and histamine release. Opioids also induce nausea and vomiting, and decrease gut motility.[9]

Neuromuscular-blocking agents: The use of these agents including vecuronium, atracurium, cis-atracurium, pancuronium lessens the patient–ventilator asynchronism, thus permitting more effective ventilation, lowers the risk for barotrauma, reduces O_2 consumption and CO_2 production, and reduces lactate accumulation. The use of paralytics, however, presents a number of disadvantages such as myopathy, excessive airways secretions, histamine release (atracurium), and tachycardia and hypotension (pancuronium). The concomitant use of corticosteroids may increase the risk for critical illness neuromyopathy.[10] Paralytic agents, when administered, may be given intermittently by bolus or continuous intravenous infusion. If a continuous infusion is used, either a nerve stimulator should be used or the drug should be withheld every four to six hours to avoid drug accumulation and prolonged paralysis. Currently the use of paralytics is usually recommended only in those patients who cannot adequately be controlled with sedation alone. Often short term paralysis is initially required (20-60 minutes) and is discontinued once patient is stabilized and pH and pCO_2 are reasonably controlled.

EFFECTS OF INTUBATION

With intubation of the severe asthmatic patient and application of positive pressure ventilation, it is usual for systemic hypotension to occur. The determinant factors of systemic hypotension are sedation, hypovolemia, and primarily lung hyperinflation.

Dynamic hyperinflation: It is important to discuss this issue before proceeding to actual ventilation. It is the failure of the lung to return to its functional residual capacity at end exhalation. It occurs when the highly increased airway expiratory resistance prolongs expiratory flow in such a way that the next breath interrupts exhalation of the inspired tidal volume, leading to end-expiratory gas trapping. The mechanisms of intrinsic positive end-expiratory pressure (PEEPi) in acute, severe asthma include:[11]

a. Deceleration of the expiratory flow (due to resistance to airflow, short expiratory time, increased postinspiratory activity of the inspiratory muscles).
b. Increased expiratory muscle activity.
c. High ventilatory demands.

In addition, there is an important cause of hyperinflation that occurs due to airway occlusion, which is less amenable to ventilator manipulation and may play the dominant role in contributing to hyperinflation in asthma. Dynamic hyperinflation is directly proportional to tidal volume (Vt) and to the degree of airflow obstruction.

Dynamic hyperinflation may further increase in the immediate post intubation period, as a result of the mechanical ventilation, even after the delivery of normal or reduced Vt. High levels of dynamic hyperinflation may cause hemodynamic compromise in a way similar to that caused by the tension pneumothorax. The large intrathoracic pressures that develop due to dynamic hyperinflation increase the right atrial pressure, leading to a decrease in venous return to the right heart. An additional mechanism of decrease in venous return may be related to the positive intrathoracic pressures throughout the respiratory cycle during mechanical ventilation. Sedation, eventually muscle relaxation, and hypovolemia (due to increased water loss or decreased water uptake) reduce the mean systemic blood pressure and cause a further decrease in venous return to the heart. The end result may be sudden cardiovascular collapse, with systemic hypotension and tachycardia. In such cases, a trial of hypoventilation (delivering of 2–3 breaths / min of 100% oxygen for few minutes) may become necessary to exclude this eventuality. With such setting of the ventilator, in the absence of pneumothorax, the mean intrathoracic pressure will fall, systemic blood pressure will rise, pulse pressure will increase, and pulse rate will fall.[4]

VENTILATION CONTROL

Controlled modes of ventilation are preferred in the immediate post intubation period. Patients in status asthmaticus not only have an excessive work of breathing but in addition, most of them are intubated and mechanically ventilated when ventilatory muscles are fatigued. Previous studies have shown that at least 24 hours are needed for complete recovery of fatigue.[9] It appears reasonable, therefore, to rest the muscles for some time in the controlled mode of ventilation before switching the ventilator to the assist mode.

Pressure control mode: Two different modes of controlled setting of the ventilator are widely used. One mode is pressure-controlled ventilation, where the airway pressure can be maintained at a predetermined level independently of any eventual changes of the mechanical properties of the respiratory system. For example, if pressure control is used with an inspiratory pressure of 30 cm H_2O, the pressure in the lung will not exceed 30 cm H_2O, even if there are occluded airways with trapped gas. Another advantage of a pressure-targeted mode is that if the airway resistance suddenly increases, the patient will not hyperinflate; however, the Vt will drop. The problem with a pressure-targeted mode is that if the airway resistance is very high, it will be difficult to deliver an effective Vt. Thus, a pressure-targeted mode will provide the safest form of ventilation, but at the expense of decreased CO_2 clearance, a lower pH, and less effective

aerosol delivery. It should also be noted that as the patient's airflow obstruction improves, a high pressure setting with a pressure-targeted mode could lead to a large Vt. Thus, as the patient improves, the pressure setting should be reduced accordingly.[12]

Volume control mode: The other method is volume-controlled ventilation, where the ventilator delivers a predetermined Vt and the airways pressure becomes the dependent variable. This provides better ventilation and aerosol delivery but increases the risk of hyperinflation. Often, we monitor plateau pressure after a volume-targeted breath as a surrogate for end-inspiratory lung volume (which should best track with the risk of barotrauma). However, the plateau pressure is an average pressure and will reflect only the pressure in open lung units. Lung areas that have high pressure in the initial part of the inspiratory cycle, and lung segments that become occluded at the end of inspiration, may still be at risk of barotrauma despite a "safe" plateau pressure. Thus, a volume-targeted ventilation mode will better ensure adequate ventilation in severe cases or with abrupt increases in airways resistance, but probably increases the risk of hyperinflation in the asthmatic patient.[12] Pressure-controlled ventilation seems more appropriate to maintain airway pressure, especially in status asthmaticus in which airways resistance varies rapidly.[9]

Positive end expiratory pressure (PEEP): The application of PEEP in status asthmaticus is controversial. In patients with emphysema, PEEP can counterbalance the intrinsic PEEP (auto-PEEP) without affecting expiratory flow because of dynamic collapse of the airways and a "waterfall effect".[13] This can be helpful in patients who are spontaneously breathing, because it improves ventilator triggering. However, in asthmatics, the site of increased resistance is in central (less collapsible) airways. Furthermore, asthmatic airways are likely to be stiff (from inflammation) and more resistant to dynamic collapse, and thus will not have the same waterfall effect as in patients with emphysema. If there is no dynamic collapse, then, in theory, the use of PEEP will increase the back-pressure to expiratory flow and result in more hyperinflation. Indeed, early physiology studies of asthmatics on ventilators demonstrated that the application of PEEP led to more hyperinflation. Thus, most review articles have not recommended the routine use of PEEP in asthmatic patients.[14] However, a recent study suggested that the physiology may be more variable, so some patients respond to PEEP with increased air trapping, some with no change in lung volume, and some with a paradoxical decrease in lung volume. This would suggest that in some patients, PEEP can be carefully applied, although commonly the practice is to use no PEEP or physiological PEEP of 3 cm H_2O during controlled ventilation.

Hypoxemia: Correction of the hypoxemia is one of the first priorities in setting the ventilator.[15] In non-complicated status asthmaticus, high V / Q ratio is the predominant mechanism and true shunt does not contribute significantly to the hypoxemia. Correction of the hypoxemia is therefore easily obtained by the administration of relatively low concentrations of supplemental oxygen. In the majority of patients, the administration of a

fraction of inspired oxygen at the level of 30–50% is sufficient to raise PaO_2 above 60 mm Hg. Failure of this level of fraction of inspired oxygen to increase PaO_2 above 60 mm Hg indicates some kind of complication (e.g. mucoid impaction atelectasis, pneumonia, or pneumothorax). Complete correction of the respiratory acidosis is not an urgent priority and, since it requires normalization of the $PaCO_2$, which may cause significant deterioration of dynamic hyperinflation, most authors prefer a carefully used buffered therapy for the correction of patient's pH. The appropriate setting of the ventilator in mechanically ventilated patients is of paramount importance to manage, and to avoid further significant increase of, lung hyperinflation. Several studies have shown that for patients in status asthmaticus, a large part of the morbidity and mortality are related to the mechanical ventilation itself rather to the disease process.[15]

In patients on controlled modes, there are three strategies that can decrease dynamic hyperinflation:

1. Decrease of VT
2. Increase of expiratory time, and
3. Decrease of resistance.

Controlled hypoventilation (permissive hypercapnia): This is the recommended ventilator strategy to reduce the degree of lung hyperinflation and provide adequate oxygenation and ventilation while minimizing systemic hypotension and barotrauma.[16] Hypoventilation can be obtained by decreasing either the tidal volume or the respiratory frequency, or both. Hypercapnia is generally well-tolerated as long as $PaCO_2$ does not exceed 90 mm Hg and acute variations in $PaCO_2$ are avoided. Low values of arterial pH are well tolerated, and slow infusions of sodium bicarbonate appear to be safe in patients with acidosis. In the immediate post intubation period, and as a result of the mechanical ventilation, especially when patients are ventilated to eucapnia, dynamic hyperinflation may further increase. In order to avoid dangerous levels of dynamic hyperinflation, the ventilator should be set to allow sufficient exhalation time (increasing the expiratory time) while continuing bronchodilator and corticosteroid treatment (decreasing resistance to expiratory flows). The increase in expiratory time can be achieved by increasing inspiratory flows at the expense of increasing peak dynamic pressures, and by the elimination of end-inspiratory pause. Although the strategy of increasing expiratory time is less powerful than controlled hypoventilation, it decreases dynamic hyperinflation considerably, and it improves cardiovascular function and gas exchange. Decreasing resistance to expiratory flows includes pharmacologic treatment to overcome asthma and an effort to decrease the external resistance related to ventilator tubing.

Dynamic hyperinflation: There are several techniques for the estimation of the level of dynamic hyperinflation. One way is to measure the end inspired volume above apneic FRC (V_{EI}).[17] Apneic FRC is determined by measuring the total exhaled volume of gas during 20–40 seconds of apnea in a paralyzed patient. V_{EI} is the sum of the tidal volume and the volume at end exhalation above FRC (Fig. 11.1). Values of V_{EI} above a threshold

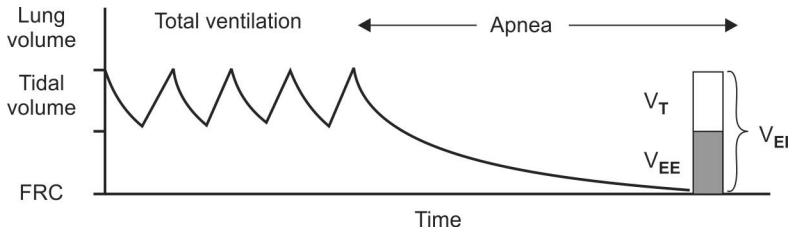

Fig. 11.1: Measurement of the end-inspired volume (V_{EI}) above apneic functional residual capacity (FRC) in order to estimate lung hyperinflation. V_{EI} is the volume of gas at the end of inspiration above FRC and is the sum of the tidal volume and the volume at end exhalation above FRC (V_{EE})

value of 20 ml/kg (1.4 L in an average adult) have been shown to predict complications of hypotension and barotrauma.[18] The need for paralysis, however, limits the use of V_{EI}.

In the mechanically ventilated patient, other estimates of the degree of dynamic hyperinflation are the determination of the end-inspiratory plateau pressure (Pplat) and the measurement of intrinsic PEEP (PEEPi).[19] To obtain both measurements, patient relaxation, but not paralysis, is necessary. Pplat is an estimate of average end-inspiratory alveolar pressures and is easily determined by stopping flow at end-inspiration (Fig. 11.2). PEEPi is the lowest average alveolar pressure achieved during the respiratory cycle and is obtained by an end-expiratory hold maneuver (Fig. 11.3). When evaluating these methods, The American College of Chest Physicians consensus conference on mechanical ventilation concluded that Pplat is the best predictor of hyperinflation in ventilated asthmatic patients and recommended that Pplat must be kept lower than 35 cm H_2O.[18]

After successful treatment and when the patient's conditions improve, the ventilator should be switched to assisted modes (pressure or volume),

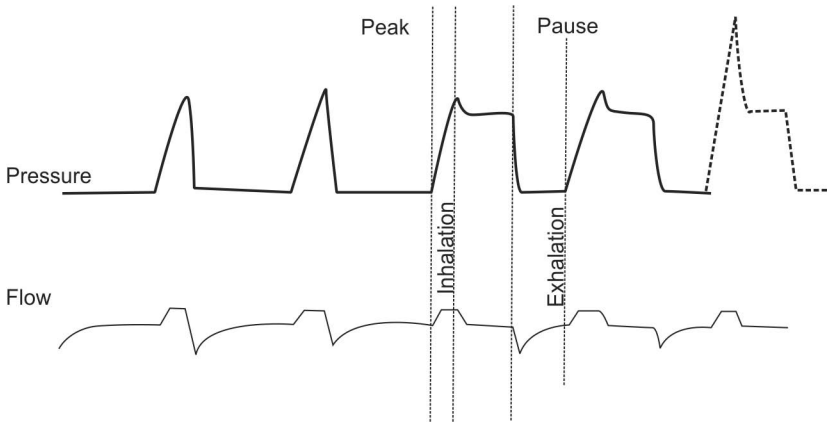

Fig. 11.2: Measurement of end-inspiratory plateau pressure, an estimate of average end-inspiratory alveolar pressures at the end-inspiration. The dotted line indicates a high peak-to-plateau gradient observed in status asthmaticus

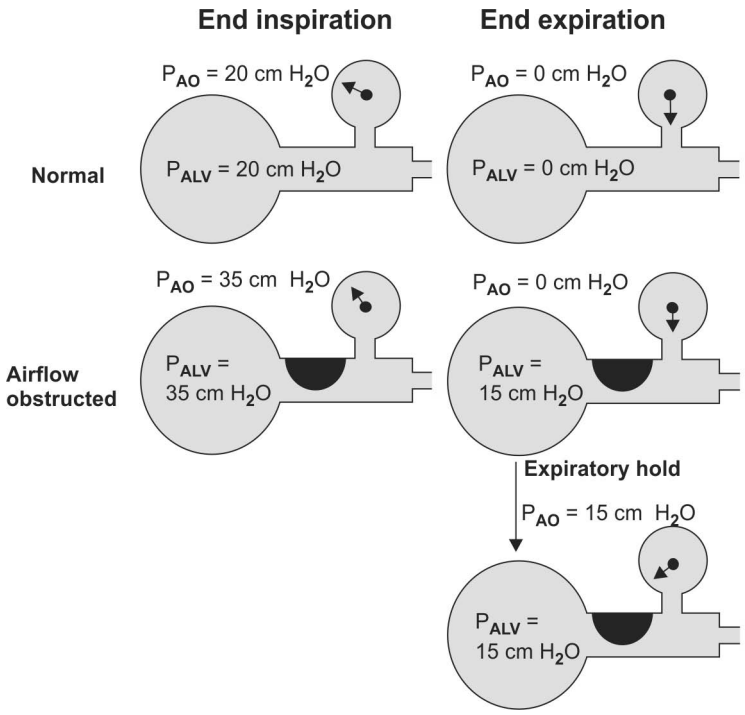

Fig. 11.3: Measurement of intrinsic positive end-expiratory pressure (PEEPi) obtained by an end-expiratory hold maneuver. In the non-obstructed patient, alveolar pressure (PALV) equals pressure at the airway opening (PAO) both at end inspiration and end expiration. In the severely obstructed patient, PALV may increase because of air trapping, and at end expiration. PALV does not equal PAO. If an expiratory hold maneuver is performed, PAO will rise, reflecting the degree of lung hyperinflation

and the process of weaning should begin. In order to improve the patient / ventilator synchronism, two issues should be taken into account, the response of ventilator to patient effort, and the response of patient effort to ventilator-delivered breath.

MEDICAL MANAGEMENT OF ASTHMA IN THE INTUBATED PATIENT

Systemic corticosteroids: Because bronchospasm continues after intubation, inhaled bronchodilators and systemic corticosteroids should be continued. Systemic corticosteroids are the gold standard of treatment in intubated asthmatic patients.[20]

Inhaled β-agonists: Inhaled β-agonists are also indicated; however, the most effective dosing is debated. The literature shows that delivery of sufficient puffs of β-agonists through an MDI using a well-designed reservoir system is cost-effective and has proved to be as effective as using a nebulizer in intubated asthmatic patients.[21]

Other bronchodilators: The clinical benefits of intravenous theophylline in intubated patients are unknown, but outcomes in hospitalized asthmatic patients in general do not appear to improve with intravenous theophylline.[5]

NONINVASIVE MECHANICAL VENTILATION

As mechanical ventilation in asthmatics is extremely complex, it may be prudent to consider options like noninvasive ventilation (NIV) in these patients. NIV often prevents intubation in patients with chronic obstructive pulmonary disease and may have a similar benefit in asthmatics.[22] The indications for initiating noninvasive ventilation in acute, severe asthma are not clearly defined, and its use is uncertain.[23] Two small prospective studies including a total of 47 such patients who on admission were either normocapnic or hypercapnic showed that a short trial of NIV improves respiratory distress and gas exchange.[24] A small randomized trial in children with severe asthma has demonstrated improvement in lung function and decreased need for hospitalization with the use of NIV.[25] However a recent Cochrane meta-analysis concluded that the use of NIV remains controversial, despite promising initial results.[26] Thus, NIV is still controversial and warrants further study with randomized controlled trials. Patients must be carefully selected. In pediatric patients, the margin of safety is low; hence NIV must be used cautiously. Commonly accepted contraindications to NIV are severe encephalopathy, severe acidosis, hemodynamic instability, cardiac / respiratory arrest, facial deformity, high risk for aspiration, severe upper gastrointestinal bleeding, and upper airway obstruction.[27]

CONCLUSION

Severe asthma causing respiratory failure is a life-threatening condition with increased morbidity and mortality. Mechanical ventilation in severe asthma is complex and requires careful personalized management. Goals of ventilation should be to provide adequate gas exchange and minimize hyperinflation while continuing therapies to reduce airway inflammation and bronchoconstriction.

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12 Chapter

Weaning from Mechanical Ventilation

Sankaran Krishnan, Praveen Khilnani

For many patients, once the need for mechanical ventilation no longer exists, the procedure can be discontinued very rapidly. This includes post-operative ventilatory support for recovery from surgery and anesthesia or uncomplicated drug overdose.

For many others, this is often a lengthy complicated process called weaning.

Weaning implies that the need for support still exists and that the patient is ventilator dependent. It is a gradual process that is begun only after there is evidence that the problem leading to the need for mechanical ventilation has resolved.

There are many guidelines and evidence based reports on weaning in adults, however specific criteria based on evidence are not yet established in children.[1-8] Many of the following recommendations or suggestions are based on cumulative data obtained from adults and children.

Pathophysiology of Ventilator Dependence

Patients require mechanical ventilatory support when the ventilatory and / or gas exchange capabilities of their respiratory system fail. This failure could be due to processes within the lung or other systems like the central nervous system (CNS) or cardiovascular system.

The term "ventilator dependent" is usually reserved for patients with a need for mechanical ventilation beyond 24 hours or by the fact that they have failed to respond during discontinuation attempts (Table 12.1).

Under these circumstances, the clinical focus should be not only on ventilator management, but also should include a search for all of the possible reasons (especially potentially reversible ones) that may explain the ventilator dependency.

Recommendation 1: In patients requiring mechanical ventilation for more than 24 hours, a search for all the causes that may be contributing to ventilator dependence should be undertaken. This is particularly true in the patient who has failed attempts at withdrawing the mechanical ventilator. Reversing all possible ventilatory and nonventilatory issues should be an integral part of the ventilator discontinuation process.

TABLE 12.1: Causes of ventilator dependency

Causes	*Description*
Neurologic controller	Central drive; peripheral nerves
Respiratory system	Mechanical loads: respiratory system mechanics; imposed loading
	Ventilatory muscle properties: inherent strength/endurance; metabolic state/nutrients/oxygen delivery and extraction
	Gas exchange properties: vascular properties and ventilation/perfusion matching
Cardiovascular system	Cardiac tolerance of ventilatory muscle work; peripheral oxygen demands
Psychological issues	

DETERMINANTS OF WEANING OUTCOME

Neurologic Issues[9]

The ventilatory pump controller or respiratory center contained in the brainstem is a rhythm and pattern generator, which receives feedback from cortical, chemoreceptive, and mechanoreceptive sensors. The failure of the central controller can be due to structural (e.g. brainstem strokes or central apneas) or metabolic (e.g. electrolyte disturbances or sedation / narcotic usage) factors. Apnea of prematurity is due to non-maturation of the respiratory center. The failure of the peripheral nerves can also be the result of either structural factors or metabolic / drug factors.

Respiratory System Muscle/Load Interactions[10-13]

Often, patients who exhibit ventilator dependence do so because there appears to be a mismatch between the performance capacity of the ventilatory pump and the load placed on it (i.e. the capacity / load imbalance hypothesis). Ventilatory pump performance may be impaired in ventilator-dependent patients because ventilatory muscles are weak from atrophy and remodeling from inactivity or sometimes overuse. Drugs (e.g. neuromuscular blockers, aminoglycosides, and corticosteroids) can also contribute to myopathy. Finally, dynamic hyperinflation can put ventilatory muscles in a mechanically disadvantageous position. Ventilatory muscle fatigue could also contribute to poor muscle performance.

The load on the ventilatory muscles is a function of ventilation demands and respiratory system mechanics (i.e. primarily compliance and resistance). Ventilation demands can increase as a consequence of increased oxygen demands in patients with sepsis and serious infections or increased dead space in patients with asthma. Compliance worsening can be a consequence of lung edema, infection, inflammation, or fibrosis and of chest wall abnormalities such as edema or even surgical dressings. Worsening resistance can be a consequence of bronchoconstriction and airway inflammation. Additional load also can be imposed by narrow endotracheal tubes and by poorly responsive ventilator demand valves.

Patients who go on to fail to respond to ventilator withdrawal attempts because of a capacity / load imbalance tend to display rapid, shallow breathing patterns.

This pattern is advantageous from an energetics perspective, but it is also associated with increased dead space and wasted ventilation, and hence with impaired CO_2 elimination.

Metabolic Factors and Ventilatory Muscle Function[14-21]

Nutrition, electrolytes, hormones, and oxygen transport are all metabolic factors that can affect ventilatory muscle function. Inadequate nutrition leads to protein catabolism and a loss of muscle performance. The normal hypoxic ventilatory response and the hypercapnic ventilatory response have been shown to deteriorate under conditions of semi-starvation. Also, overfeeding can impair the ventilator withdrawal process by leading to excess CO_2 production, which can further increase the ventilation loads on ventilatory muscles. Phosphate deficiency has been associated with respiratory muscle weakness and ventilator withdrawal failure. Magnesium deficiency has also been reported to be associated with muscle weakness, and bicarbonate excretion from inappropriate overventilation, often occurring in BPD (bronchopulmonary dysplasia) patients with chronic baseline hypercapnia can impair ventilator withdrawal efforts as the patient has a diminished capacity to compensate for hypercapnia.

Severe hypothyroidism and myxedema directly impair diaphragmatic function and blunt ventilatory responses to hypercapnia and hypoxia. Other hormonal factors that are important for optimal muscle function include insulin / glucagon and adrenal corticosteroids.

Gas Exchange Factors

Gas exchange abnormalities can develop during ventilatory support reductions since various lung diseases produce ventilation perfusion imbalances and shunts.

Cardiovascular Factors

Suggested mechanisms include the following:

1. Increased metabolic demands, and hence circulatory demands, that are associated with the transition from mechanical ventilation to spontaneous breathing in patients with limited cardiac reserve.
2. Increase in venous return as the contracting diaphragm displaces blood from the abdomen to the thorax.
3. The increased left ventricular afterload that is imposed by negative pleural pressure swings.

Psychosocial Factors

Psychological factors may be among the most important non-respiratory factors leading to ventilator dependence. Fear of the loss of an apparent life support system as well as social / familial / economic issues, particularly in our set-up all may play a role.

Stress can be minimized by frequent communication among the staff, the patient, and the patient's family. Environmental stimulation using television, radio, or books also appears to improve psychological functioning. Ambulation (though impractical at times) using a portable ventilator (or bagging) has been shown to benefit attitudes and outlooks in long-term ventilator-dependent patients.

Criteria to Assess Ventilator Dependence[5-7, 22-24]

The process of discontinuing mechanical ventilatory support begins with a recognition of adequate recovery from acute respiratory failure.

Thereafter, careful clinical assessments are required to determine the patient's readiness for subsequent discontinuation of ventilatory support and, ultimately, extubation.

To facilitate this process, investigators have focused on identifying objective criteria to determine the answers to the following questions:

When can efforts to discontinue ventilation be initiated? What assessment strategies will best identify the patient who is ready for ventilator discontinuation? When should extubation be carried out, and how can extubation outcome be best predicted?

Evidence to answer these questions comes largely from observational studies in which a certain parameter (or set of parameters) is compared in a group of patients who either successfully or unsuccessfully have been removed from the ventilator. The general goal of these studies is to find "predictors" of outcome. Evaluating the results from these types of studies can be difficult for several reasons.

First, the "aggressiveness" of the clinician / investigator's weaning and discontinuation philosophy needs to be understood, as it will affect the performance of a given predictor. Second, a number of methodological problems exist with most of these observational studies. For instance, patients are recruited into these studies because investigators believe that there is some reasonable chance of success for ventilator discontinuation. These "entry" criteria often include some form of clinical judgment or intuition, making results from one study difficult to compare to another. Third, assessed outcomes differ from study to study. Some investigators have examined successful tolerance of a spontaneous breathing trial (SBT), others have used permanent discontinuation of the ventilator, and others have combined successful discontinuation and extubation.

Based on these (mostly adult) studies, the following recommendations are suggested:

Recommendation 2: Patients receiving mechanical ventilation for respiratory failure should undergo a formal assessment of discontinuation potential if the following criteria are satisfied:

1. Evidence for some / all reversal of the underlying cause for respiratory failure.
2. Adequate oxygenation (e.g. PaO_2 / FiO_2 ratio > 150 to 200; requiring positive end-expiratory pressure [PEEP] $\leq$ 5 to 8 cm H_2O; $FiO_2 \leq 0.4$ to 0.5); and pH (e.g., $\geq$ 7.25).

TABLE 12.2: Criteria used in weaning/discontinuation studies[25-29]

Criteria	*Description*
Objective measurements	Adequate oxygenation ($PO_2 \geq 60$ mm Hg on $FiO_2 \leq 0.4$; PEEP $\leq 5 – 10$ cm H_2O; $PO_2/FiO_2 \geq 150–300$);
	Stable cardiovascular system (e.g. HR ≤ 140; stable BP; no (or minimal) pressors)
	Afebrile (temperature < 38°C)
	No significant respiratory acidosis
	Adequate hemoglobin (Hgb $\geq$ 8–10 g/dl)
	Adequate mentation (e.g., arousable, GCS ≥ 13, no continuous sedative infusions)
	Stable metabolic status (acceptable electrolytes)
Subjective clinical assessments	Resolution of disease acute phase; physician believes discontinuation possible; adequate cough

*Hgb = hemoglobin; HR = heart rate; GCS = Glasgow coma scale

3. Hemodynamic stability, as defined by the absence of clinically significant hypotension (i.e. a condition requiring no vasopressor therapy or therapy with only low-dose vasopressors such as dopamine or dobutamine, < 5 μg / kg / min).
4. The capability to initiate an inspiratory effort.

The decision to use these criteria must be individualized. Some patients not satisfying all of the above criteria (e.g. patients with chronic hypoxemia / hypercapnia) may be ready for attempts at the discontinuation of mechanical ventilation (Table 12.2).

Recommendation 3: Formal discontinuation assessments for patients receiving mechanical ventilation for respiratory failure should be performed during spontaneous breathing rather than while the patient is still receiving substantial ventilatory support. An initial brief period of spontaneous breathing can be used to assess the capability of continuing onto a formal SBT (Table 12.3).

The criteria with which to assess patient tolerance during SBTs are the respiratory pattern, the adequacy of gas exchange, hemodynamic stability, and subjective comfort. The tolerance of SBTs lasting 30 to 120 minutes should prompt consideration for permanent ventilator discontinuation.

Recommendation 4: **The removal of the artificial airway from a patient who has successfully been discontinued from ventilatory support should be based on assessments of airway patency and the ability of the patient to protect the airway.**

Extubation failure can occur for reasons distinct from those that cause discontinuation failure. Examples include upper airway obstruction or the inability to protect the airway and to clear secretions. The risk of postextubation upper airway obstruction increases with the duration of mechanical ventilation, female gender (in adults, not studied in children), trauma, size of ET(endotracheal) tube, presence / absence of cuff and

TABLE 12.3: Criteria used in several large trials to define tolerance of an SBT[25-29]

Criteria	*Description*
Objective measurements indicating tolerance/success	Gas exchange acceptability ($SpO_2 \geq 85–90\%$; $PO_2 \geq 50–60$ mm Hg; pH ≥ 7.32; increase in $PaCO_2 \leq 10$ mm Hg); Hemodynamic stability (HR < 120–140 beats/min; HR not changed > 20%; systolic BP < 180–200 and > 90 mm Hg; BP not changed > 20%, no pressors required) Stable ventilatory pattern (e.g. RR d" 30–35 breaths/min; RR not changed > 50%)
Subjective clinical assessments indicating intolerance/failure	Change in mental status (e.g. somnolence, coma, agitation, anxiety); Onset or worsening of discomfort Diaphoresis Signs of increased work of breathing (use of accessory respiratory muscles, and thoraco-abdominal paradox)

*HR = heart rate; SpO_2 = hemoglobin oxygen saturation

repeated or traumatic intubation. The capacity to protect the airway and to expel secretions with an effective cough is vital for extubation success. Airway assessments generally include noting the quality of cough with airway suctioning, the absence of "excessive" secretions, or the frequency of airway suctioning (e.g. every 2 hours or more).

Managing the Patient Who Has Failed an SBT

Recommendation 5: Patients receiving mechanical ventilation for respiratory failure who fail an SBT should have the cause for the failed SBT determined. Once reversible causes for failure are corrected, and if the patient still meets the criteria, subsequent SBTs should be performed every 24 hours.

Recommendation 6: Patients receiving mechanical ventilation for respiratory failure who fail an SBT should receive a stable, nonfatiguing, comfortable form of ventilatory support.There are a number of ventilator modes that can provide substantial ventilatory support as well as the means to reduce partial ventilatory support in patients who have failed an SBT (Table 12.4). A key question, however, is whether attempts at gradually lowering the level of support (weaning) offer advantages over a more stable, unchanging level of support between SBTs. The arguments for using gradual reductions are:

1. That muscle conditioning might occur if ventilatory loads are placed on the patient's muscles and
2. That the transition to extubation or to an SBT might be easier from a low level of support than from a high level of support. Data supporting either of these claims, however, are few. However, maintaining a stable level of support between SBTs reduces the risk of precipitating ventilatory muscle overload from overly aggressive support reduction. It also offers a significant resource consumption advantage in that it

TABLE 12.4: Modes of partial ventilator support[30-38]

Mode	*Patient work adjusted by*
SIMV	Number of machine breaths supplied (i.e. the fewer the number of machine breaths, the more spontaneous breaths are required)
PSV	Level of inspiratory pressure assistance with spontaneous efforts
SIMV + PSV	Combining the adjustments of SIMV and PSV
VS	PSV with a "guaranteed" minimal tidal volume (PSV level adjusts automatically according to clinician tidal volume setting)
VAPS (PA)	PSV with "guaranteed" minimal VT (additional flow is supplied at end inspiration if necessary to provide clinician VT setting)
MMV	SIMV with a "guaranteed" $\dot{V}E$ (machine breath rate automatically adjusts according to clinician $\dot{V}E$ setting)
APRV	Pressure difference between inflation and release (i.e. the less the pressure difference, the more spontaneous breaths are required)

SIMV = Synchronized intermittent mandatory ventilation; PSV = Pressure support ventilation; VS = Volume support; VAPS (PA) = Volume assured pressure support (pressure augmentation); MMV = Mandatory minute ventilation; APRV = Airway pressure release ventilation

requires far less practitioner time. It has been demonstrated that the daily SBT with stable support between tests permitted the most rapid discontinuation. What has not been addressed, however, is whether gradual support reductions coupled with daily SBTs offer any advantages.

Procedure of Weaning from Mechanical Ventilation (Flow chart 12.1)

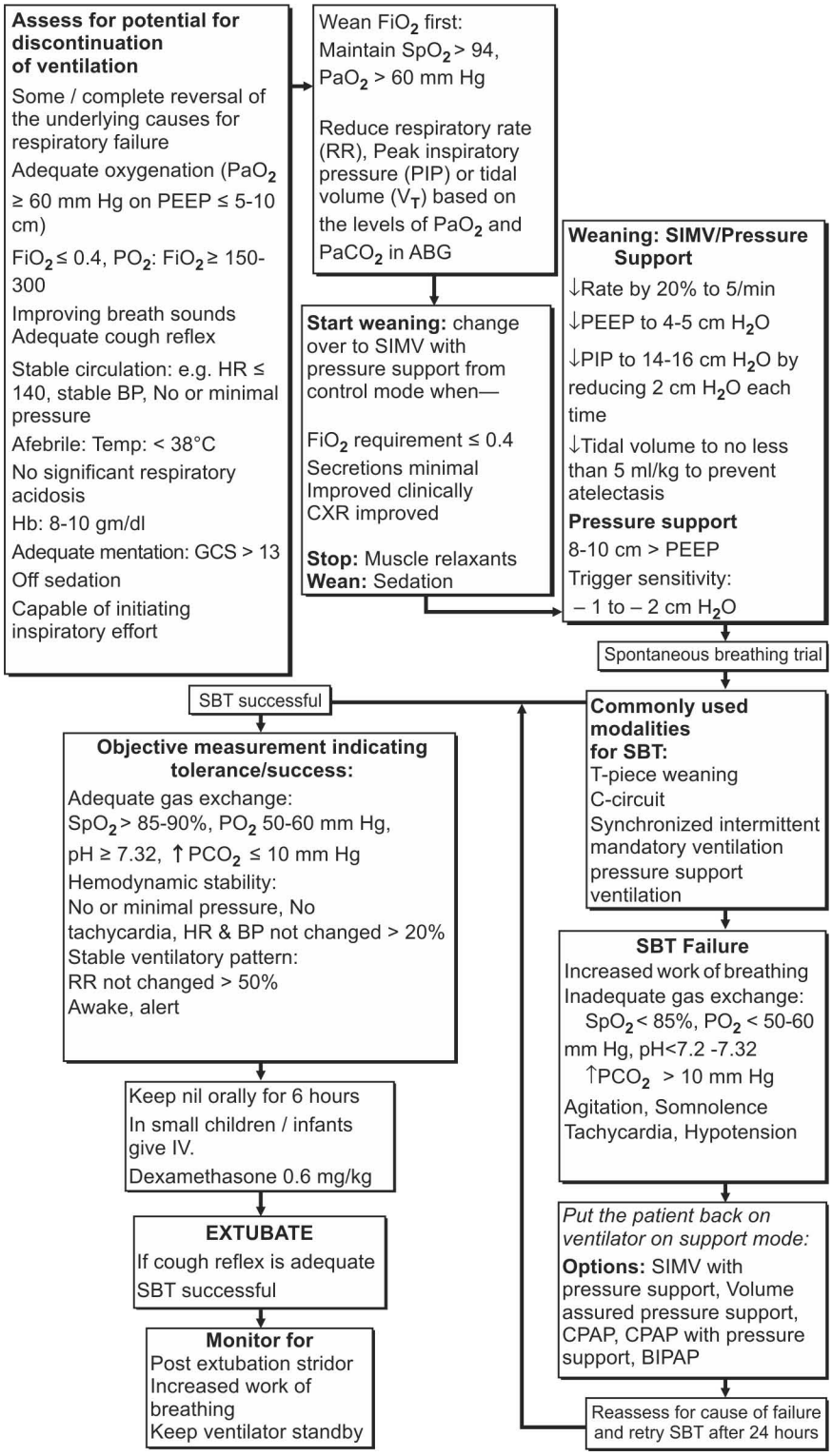
Process of weaning begins at the time of initiation of ventilation (i.e. minimal ventilatory settings to keep blood gases and clinical parameters within acceptable limits, although these settings will be very high).

If such procedure is followed then ventilatory settings would be reduced once the primary pathology / condition that led to ventilation is improving.

How do we know if the Condition is improving?

- Improving general condition, fever etc.
- Decreasing FiO_2 requirement
- Improving breath sounds
- Decreasing endotracheal secretions
- Improving chest X-rays
- Decreased chest tube drainage, bleeding / air bubbles (as the case may be)
- Improved fluid and electrolyte status (no overload or dyselectrolytemia)
- Improving hemodynamic status
- Improving neurological status, muscle power, airway reflexes / control.

Flow chart 12.1: Weaning from mechanical ventilation



Described weaning criteria such as maximal negative inspiratory force, vital capacity measurement are usually impractical.

In pediatrics and neonatal age group, weaning criteria are generally clinical. Ventilatory support in general should be weaned in small percentages (including rates, pressures, volumes and inspired oxygen determining the overall ventilatory support).

Weaning Modes

Three commonly used methodologies include:

1. *T-piece weaning:*[30-34] Patient is made to breathe spontaneously off the ventilator via a T-piece through which O_2 is administered, for increasing intervals of time as tolerated and extubated when criteria for extubation are met.
   Advantages: Simple, no "technical expertise" needed, improves muscle recruitment and endurance.
   Disadvantages: In small children, the resistance offered by the tube and circuit limit use of this mode. Close monitoring of gas exchange and muscle fatigue is needed, as the muscle training is "abrupt". Diaphragm-intercostal dysynchrony is sometimes seen, again especially in small children.
2. *Intermittent mandatory ventilation*
3. *Pressure support ventilation*

Intermittent mandatory ventilation(IMV): IMV with continuous flow ("conventional" weaning). Popularized in neonatal intensive care units (NICUs). Ventilator rate is gradually decreased allowing baby's own respiratory rate to take over. Baby is weaned to minimal rates (6-8), put on CPAP (Continuous positive end-expiratory pressure) briefly and extubated.

Advantages: Simple, lot of experience and data prove efficacy, less technical know-how. Avoidance of paralysis / sedation, respiratory alkalosis, muscle atrophy.

Disadvantages: Muscle training not optimal, not suitable in older children, requires a continuous flow circuit. Asynchronised, so breath stacking possible.

SIMV

Sychronized mode, prevents breath stacking / barotraumas. Pre-set rate and volume delivered to patient, however breaths are synchronized with patient's spontaneous efforts by a servo-controlled mechanism. There is a window period around each breath which the ventilator uses for "looking for" a spontaneous breath – the SIMV window, after which the ventilator breath is delivered. During weaning, the set SIMV rate is gradually reduced as patient's spontaneous breaths become adequate. Otherwise similar to IMV. Does not need continuous flow. Servo controlled.

Pressure Support (PS)[35-38]

This is an assist mode, pressure or flow triggered, pressure limited, flow-cycled method. Inspiration ends when a predetermined percentage (usually 25%) of the patients peak inspiratory flow is reached. Patient controls inspiratory flow, time, frequency.

There are three forms of PS ventilation:

a. *PSmax*—As a stand alone form of ventilation. Uses high levels initially depending on the patient's tidal volume and compliance, which is then gradually weaned.
b. *At low levels with SIMV*.
c. *At low levels with PEEP/CPAP* to overcome resistance of the system pre-extubation.

Advantages: Permits patient to acquire larger TV (tidal volume) at same level of effort (as in patients with increased airway pressures, decreased compliance), neuromuscular problems (decreases resistance offered by the system). Decreases work of breathing.

Disadvantages: If used without SIMV, patient has to be breathing spontaneously. Needs back-up expired MV (Minute ventilation) alarms. Servo controlled, so equipment complicated / expensive.

SIMV with PS: Seems to be ideal for post-neonatal to older children. This mode combines advantages of mandatory synchronized breaths with gradually increasing assisted breaths. Traditionally, the mandatory breaths have a preset TV (SIMV with PS, volume control). In the newer servo ventilators, the mandatory breaths could also be preset pressure controlled (SIMV with PS, pressure control). This mode is, of course dependent on the efficacy of the microchip processor.

Volume Assured Pressure Support (VAPS)

Newer mode, the flow triggered pressure supported breaths also guarantee a minimum preset MV (minute ventilation), thus improving the work of breathing further.

CPAP—Weaning mode pre-extubation. It is often used to overcome resistance of tubing on spontaneous breathing. This mode should not be used for a prolonged period of time as it can lead to muscle fatigue. This mode can also be used with PS.

Goals of Mechanical Ventilation during Weaning

Optimization of ventilatory muscle function. Weaning returns the breathing loads to the patient's ventilatory muscles. The idea is to reduce loads to tolerable levels, and the muscles should have adequate strength and endurance. There is a fine balance between need for ventilation which is imposed by the demands resulting from disease and spontaneous ventilation.

Demands could be in the form of:

1. Pressure loads from decreased lung compliance or increased airway resistance, and

2. Ventilatory loads from increased need for alveolar ventilation or increased dead space.

These demands need to be balanced by the patient's ventilatory capabilities—normal neural drive and adequate muscle function, i.e. strength and endurance. Impaired muscle function may result from residual muscle fatigue, malnutrition and direct effects of the primary disease.

Patient-ventilator Synchrony

Un-coordinated ventilatory pattern increases O_2 consumption and CO_2 production, necessitating a higher minute ventilation. This dysynchrony can lead to an erroneous overuse of sedation. Therefore a pattern that is synchronized with the patient's mechanoreceptors and inspiratory flow demands is desirable. Apart from ventilatory parameters, the high-pressure loads are imposed by ventilatory circuits, endotracheal tubes and demand valves.

Pre-requisites to Weaning

Clinical Lab "Technical indices"
Respiratory Systemic
Neuro. Muscle Nutrition Psychological
Respiratory: WOB–RR, retractions, accessory muscles use, sensorium.

Laboratory

$PO_2 > 60$ on $FiO_2 < 0.4$,
A-a gradient < 350 on FiO_2 of 1.0,
$PO_2 / FiO_2 > 200$

"Technical indices": (Not well established in children):
1. Crying vital capacity (VC) > 15 ml/kg
2. MIF (maximal inspiratory force) > 45
3. Qs/Qt < 20%
4. Normal oxygenation and CO_2 elimination on minimal PPV (SIMV < 4/m, PEEP/CPAP < 5) with $FiO_2 < 0.4$ predict successful weaning and extubation in majority of patients.

Ventilatory pump indices in older children and adults:
1. VC > 10-15 ml/kg
2. MIF (maximal inspiratory force) > 30
3. MV (minute ventilation) < 10 L/m
4. MVV (maximal voluntary ventilation) > twice resting MV
5. Thoracic compliance > 25
6. Airway occlusion pressure (P0.1) < 6
7. RR (respiratory rate) < 25
8. TV (tidal volume) > 300.

Weaning Methodology

There are no set protocols supported by any pediatric studies.
A suggested practical protocol followed at authors institution is as follows:

When FiO_2 requirement is down to 0.4 or lower, improvement in secretions, and chest X-rays, improving clinical condition, muscle relaxant drip (if used) is stopped and sedation can be slowly weaned.

One should change control mode (or PRVC) to SIMV mode with pressure support. If already on SIMV mode with pressure support, then SIMV rate can be reduced by 20 percent.

Pressure support can be set at 10-15 cm above PEEP so that the spontaneous breaths can be adequately supported.

Trigger sensitivity should be 0 to negative one, so that the patient can easily generate a negative pressure to trigger(initiate) the ventilator breath or flow.

Following weaning guidelines can be followed:

1. *Decrease FiO_2 to keep $SpO_2 > 94$*
2. *Decrease the PEEP to 4-5 gradually by decrements of 1-2 cm H_2O*
3. *Decrease the SIMV rate to 5 (by 3-4 breaths/min)*
4. *Decrease the PIP (to 20 cm H_2O, by reducing 2 cm H_2O each time/Tidal volume, to no less than 5 ml/kg to prevent atelectasis (usually guided by blood gases)*
5. *Ventilator (SIMV) rate and PIP (or tidal volume) can be changed alternately*.

If at any point patient's oxygen requirement increases greater than 0.6, or spontaneous ventilation is fast or distressed with accessory muscle use (increased work of breathing), patient gets lethargic, hypercarbia on blood gas, weaning process should be paused and the support level increased. Patient may not be ready.

Goal is to decrease what the ventilator does and see if the patient can make up the difference without desaturations / hypercarbia / significant tachypnea and respiratory distress (For example, If patient's SIMV was reduced from 20 / min to 15 / min and the patient's spontaneous rate is increased from 25 to 50, this patient may need more time on the ventilator).

EXTUBATION

Most patients can be weaned to SIMV of 5 and extubated,some will need pressure support 5-10 above PEEP with CPAP, while others may need CPAP 5 cm H_2O before extubation, with or without spontaneous breathing trials (SBT) with T piece. SBT[39] with C circuit can be given for short periods of time (15 min) to assess the patient effort before extubation.

Extubation can generally be performed when the following criteria are met:

1. Control of airway reflexes, minimal secretions
2. Patent upper airway (air leak around tube?)
3. Good breath sounds
4. Minimal oxygen requirement < 0.3 with $SpO_2 > 94$
5. Minimal rate 5 / min
6. Minimal pressure support (5-10 above PEEP)
7. "Awake " patient.

Usually if patient can be well for 24 hours after extubation with residual distress settling down as well as no significant increase in oxygen requirement, it is considered a success, and one may communicate with the family accordingly.

Common Causes of Extubation Failure

Airway issues
Secretions with weak cough
Stridor due to edema, inflammation
Bronchospasm
Atelectasis or significant residual lung disease
Too much sedation or neurological reason for being comatose
Residual paralysis due to muscle relaxation
Muscle weakness
Hemodynamic instability, requirement for significant inotropic support
Fluid overload / pulmonary edema
Electrolyte abnormalities such as
Low potassium, low sodium, abnormal calcium, magnesium, phosphorus.

DONT'S

Do not wean pressure or volume parameters if the FiO_2 is 1.
Don't keep PEEP to high level (7 or 9cm H_2O, remember to wean it !) if the FiO_2 is already down to 30.

Summary

General principles of weaning:

1. Weaning should be initiated only after the primary disease / alteration in physiologic status which necessitated ventilation to be reversed.
2. Weaning modes which permit the patient's respiratory system to take over are preferred to abrupt withdrawal techniques in children.
3. Gradual weaning permits muscle strengthening and decreases fatigability.
4. Careful monitoring of patient's clinical and oxygenation / ventilation status essential.
5. Triggering is the term used to describe the process by which the patient initiates enough negative inspiratory force to overcome resistance imposed by the tube / circuit and an additional preset resistance. Triggering is used in patient assist modes of weaning including pressure support modes. Triggering can be pressure or flow triggered.
6. There is no ideal weaning mode. Like all forms of ventilatory therapy, weaning is a learnt art rather than a science. One should get comfortable with a few modes and use it judiciously rather than experimenting with all available newer modes.

Conclusion

Weaning is an art. It needs to be clinically gauged and GRADUAL. Most children with short term ventilation can be weaned with or without a set protocol.

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13 Chapter

Complications of Mechanical Ventilation

Praveen Khilnani

Pediatric intensivist needs to be aggressive in use of mechanical ventilation. However, it is recommended to be twice as aggressive in weaning the ventilatory support off when the condition for which it was originally initiated is better. Nevertheless, for the time mechanical ventilation is required, it is not free of adverse effects. Following discussion deals with various adverse effects that are associated with mechanical ventilation in a critically ill child.

Numerous complications may contribute to patient morbidity and mortality:

1. Related to increased airway pressures and lung volume:
   - *Barotrauma/Volutrama:* Pulmonary interstitial emphysema, pneumothorax, pneumopericardium, pneumoperitoneum, subcutaneous emphysema
   - Decreased cardiac filling and poor perfusion
   - Other organ dysfunction; renal, hepatic, CNS
   - Pulmonary parenchymal damage
   - Adverse effects on gas exchange
   - Increased extravascular lung water.
2. Related to endotracheal / tracheostomy tube:
   - Tracheal mucosal swelling, ulceration or damage
   - Sinusitis / middle ear infection (nasal ET tubes)
   - Laryngeal edema, subglottic stenosis
   - Granuloma formation leading to airway obstruction.
3. Nosocomial infections:
   - Ventilator associated pneumonias
   - Sepsis.
4. Pulmonary circulation:
   - Increased pulmonary vascular resistance
   - Compression of alveolar vessels.
5. Mechanical operational problems:
   - Mechanical ventilator / compressor failure / alarm failure
   - Inadequate humidification.
6. Other systems:
   - Decreased hepatic blood flow
   - Decreased cerebral venous drainage.

Mechanical ventilation has diverse effects; some beneficial and others adverse. Beneficial and adverse effects can occur simultaneously. The beneficial effects in the lung are related to improvements in pulmonary mechanics, gas exchange, and hemodynamics.

Adverse effects are mainly related to: (i) Consequences of positive intrathoracic pressure, and (ii) Injury to the airway. These injuries will be discussed in detail.

Airway Injury from Mechanical Ventilation

The presence of a tracheal tube traversing the upper airway can be associated with significant airway injury. Oropharyngeal and nasopharyngeal injuries are rare.

Ulceration of the alae nasi from pressure necrosis may occur following prolonged nasotracheal intubation, particularly if the skin perfusion of the ala nasi is compromised by very tight taping. Similar ulceration may occur at the angles of the mouth from tight taping of tracheal tubes.

Similarly, injuries in the subglottic region may range from minor swelling to major ulceration. Healing of the severe injuries may lead to scarring, granuloma formed with airway obstruction, which may be partial or complex. *The majority of subglottic tracheal lesions are due to compression of the tracheal mucosa by the endotracheal cuffs.* High pressure cuffs, cardiovascular instability, upper respiratory tract infection, duration of intubation, and head and neck movement all increase the risk of tracheal injury.

Airway injury can also result from suction catheters. Necrotizing tracheobronchitis is a severe form of airway injury in patients on mechanical ventilation that is characterized by extensive ulceration and mucosal damage. The sequelae of tracheal injuries include tracheal stenosis, tracheomalacia, tracheoesophageal fistula, and tracheoinnominate artery fistula.

Injury to the airway can often be prevented by attention to detail:

- The endotracheal tube should be of the proper size with a cuff leak around it at < 20 cm H_2O positive pressure
- Excessive pressure on the skin should be avoided while taping the endotracheal tube
- Excessive patient movement should be prevented by adequate sedation and restraints
- Suctioning should be gentle, preferably with a catheter with multiple side holes
- Silicon catheters should not be routinely advanced beyond the tip of the endotracheal tube.

Effects on the Lung

Adverse effects of mechanical ventilation on the lung may be due to:

1. High airway pressures
2. Overdistention of the alveoli
3. Altered mucociliary clearance
4. Lung water clearance
5. Oxygen toxicity.

The adverse effects of positive pressure ventilation may be manifested as:

1. Parenchymal injury
2. Altered ventilation-perfusion relationship leading to impaired gas exchange
3. Increased risk for infection.

Increased airway pressure may cause hyperinflation of alveoli and predispose to alveolar rupture. Hyperinflation may increase alveolar dead space, impair cardiac filling, and compress alveolar vessels. "Pulmonary barotrauma" is a loose term that encom-passes many forms of parenchymal injury. *Volutrauma (injury due to high tidal volume and stretch related injury) is being commonly recognized.* Alveolar rupture from overdistended alveoli is the most common manifestation of pulmonary barotrauma.

Air leak may occur from the lung into the pleura (pneumothorax), the interstitium (pulmonary interstitial emphysema, PIE), the mediastinum (pneumomediastinum), and the subcutaneous tissue (subcutaneous emphysema).

Even though the term implies high airway pressures as the main mechanism of parenchymal injury, pulmonary barotrauma is often multifactorial. The physiological consequences of extra-alveolar air range from inconsequential to life-threatening.

A pneumothorax may be small and inconsequential or may be large and tense. Tension pneumothorax requires immediate evacuation.

PIE may decrease lung compliance and increase pulmonary vascular resistance.

Pneumomediastinum requires careful observation. The natural tendency of pneumomediastinum is to track along fascial planes either cephalad to produce subcutaneous emphysema of caudad to produce pneumoperitoneum or pneumoretroperitoneum.

Pneumomediastinum rarely requires evacuation.

Pneumopedcardium can range from a minimal, inconsequential amount of air to life-threatening cardiac tamponade.

Cardiovascular compromise is an indication of immediate evaculation of pericardial air.

A special form of pulmonary air leak is a bronchopleural fistula, where a fistulous track develops between the bronchus and the pleural space. This results in an almost continuous flow of air from the airway into the pleural space.

The fistulous flow is wasted ventilation and may result in hypercarbia. Attempts to increase minute ventilation by increasing tidal volume may only serve to increase the leak from the fistula. Attempts to decrease airway pressures with conventional ventilation are not possible without compromising gas exchange, high frequency ventilation may be tried.

Prevention of Barotrauma

The principal factors that can be controlled in an effort to minimize barotrauma are airway pressures and lung volumes. As long as acceptable gas exchange is maintained, every effort must be made to minimize tidal volumes and airway pressures. Hyperinflation must be avoided. When

lung disease is severe, hypercarbia may be tolerated (*Permissive hypercapnea*) provided the arterial pH is adequate (> 7.2). Inspired oxygen concentration should be maintained at nontoxic levels usually < 0.5.

Effects on Circulatory System

The cardiovascular effects of positive intrathoracic pressure are complex and depend on the underlying lung disease, uniformity of lung disease, transmission of airway pressure to the pleural space, and lung volume. Coumand was one of the first to demonstrate that positive pressure ventilation decreased cardiac output.

Positive intrathoracic pressure impedes right ventricular filling by decreasing the pressure gradient to venous return. Positive airway pressure also increases pulmonary vascular resistance, provided the airway pressure exceeds left atrial or critical closing pressure.

Positive intrathoracic pressure has also been shown to decrease left ventricular afterload. The net effect is a combination of all the effects mentioned above and the reflex cardiovascular adjustments that accompany these changes. *Mechanical ventilation may also decrease urine output, hepatic, portal venous, and mesenteric perfusion.* Many of these effects can be offset by volume loading with fluid boluses.

Nosocomial Pneumonias

Nosocomial pneumonias, sepsis, nosocomial sinusitis can occur with prolonged ventilation. Pseudomonas and gram-negative enteric organisms are commonly colonizing the ventilatory circuit, therefore use of disposable circuits as well as change of circuit (upon visible soiling) may reduce the colonization and chances of nosocomial pneumonias. This issue is discussed in the chapter on Nosocomial Infections.

COMPLICATIONS RELATED TO ADJUNCTIVE THERAPIES

Patients who are mechanically ventilated almost invariable require sedation and analgesia. The physician should be well versed with the adverse effects of the agents used. Most sedative agents result in systemic vasodilatation and depress the cardiovascular system, resulting in hypotension. This is especially prominent in those who are hypovolemic or have an already depressed myocardium.

Since these agents may be used continuously for prolonged periods, there may be tachyphylaxis, requiring escalating doses to provide the same effect. In addition, there may also be the development of dependence, which can result in withdrawal symptoms unless the drug is tapered.

Some patients also require neuromuscular blockade while ventilated. Sustained use of neuromuscular blockers (NMB's) may result in prolonged weakness. This problem is commonly associated with the use of some NMB's in conjunction with steroids. NMB's should be used only when absolutely essential and the patient should be monitored adequately (with Train of Four stimulation) to ensure that excessive dosage is avoided. If

Train of Four stimulation is not possible, then the NMB can be stopped once daily until there is evidence of recovery from blockade, before being reinstituted.

Mechanical Misadventures

Various problems can occur during mechanical ventilation, including ET tube obstruction, ET tube migration, disconnection, unplanned extubation and equipment failure.

Healthcare providers should be aware of these issues and monitor the patients closely so that such instances can be prevented or minimized.

SUMMARY

Common adverse effects of mechanical ventilation include skin irritation by endotracheal tube tape, tracheal suction injury, airway edema, baro/volutrauma, cardiovascular effects and nosocomial pneumonias.

Most of them can be recognized early, or preferably, can be prevented by attention to detail. Recently permissive hypercapnea and low tidal volume ventilation have been shown to improve outcomes in patients with acute respiratory distress syndrome (ARDS) and minimize volutrauma related lung injury. Endotracheal suctioning should be under sterile precautions and gentle at the level above the distal tip of the endotracheal tube. Chronic lung disease, oxygen toxicity and subglottic/tracheal stenosis may still be seen despite all preventive efforts due to critical condition of the child requiring cuffed tube, high airway pressures and high FIO_2.

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14 Chapter

Non-Invasive Ventilation

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Intubation and mechanical ventilation are frequently necessary to treat critically-ill infant or child who develops hypoxemia and respiratory failure. Placement of an endotracheal tube and initiation of mechanical ventilation predisposes to potential complications, such as nosocomial infection and tracheal injury as well as difficulties with sedation of an intubated child. A significant mortality and morbidity is induced by baro- and volutrauma, as well as by nosocomial pneumonia associated with invasive ventilation by endotracheal tube or tracheotomy. NIV using natural mechanisms of respiratory physiology is designed to reduce the lung injury and side effects from mechanical ventilation.

Ventilatory support delivered without establishing an artificial endotracheal airway, is termed non-invasive ventilation.

Traditionally, non-invasive ventilation has been administered with the use of devices that apply intermittent negative extrathoracic pressure. The advent of positive pressure ventilation that is delivered through a nasal or face mask has greatly expanded the use of non-invasive ventilation. Such ventilation has a role in the management of acute and chronic respiratory failure in many patients.

Role of Spontaneous Breathing in Respiratory Physiology

During the inspiratory phase of spontaneous breathing, intrathoracic pressure is negative. The action of the diaphragm and airway anatomy favor ventilation to well-perfused dependent zones of the lung, assuming a ventilation perfusion ratio (VA / Qp) of approximately 1 in normal conditions. Positive pressure controlled ventilation or diaphragmatic palsy inversely promotes non-dependent zones ventilation, while dependent (well perfused) zones are less ventilated. V_A / Qp ratio becomes inhomogeneous with improvement in non-dependent zones and venous admixture in dependent zones. This mechanism drives a decrease in arterial oxygenation that can be restored or avoided with NIV.

MECHANISM OF IMPROVEMENT WITH NON-INVASIVE VENTILATION

Several theories have been proposed to explain why intermittent NIPPV is effective. One possible explanation is that intermittent resting of clinically fatigued muscles improves respiratory muscle function. During non-

invasive ventilation, diaphragmatic electromyography activity and respiratory muscle work are reduced. NIPPV also improves lung compliance in patients with neuromuscular or chest wall disease possibility by re-expanding areas of microatelectasis. Another possible explanation is that by preventing nocturnal hypoventilation, nocturnal NIPPV prevents the blunting of the central ventilatory drive that occurs with hypercapnia.

Advantages of NIPPV

Bi-level positive airway pressure (BIPAP) has a low impact on pulmonary circulation, improve oxygenation and recruitment when continuously used. When spontaneous ventilation with or without controlled-ventilation can be maintained, a much lower level of sedation is required. Light sedation has several advantages: reducing interference with hemodynamic functions, avoiding respiratory muscles atrophy, and allowing active mobilization and active cough with a better clearance of secretions. Some studies in adults have shown a decreased incidence of nosocomial pneumonia in NIPPV when compared with all modes of ventilation associated with endotracheal intubation.

Indications for NIPPV

Acute Diseases

- Acute lung injury
- Lung infection
- Acute pulmonary edema
- Bronchiolitis.

Chronic Diseases

- Obstructive pulmonary diseases
- Obstructive sleep apnea
- Cystic fibrosis
- Neuromuscular diseases
- Anterior horn cell disease
- Guillain-Barré syndrome
- Myasthenia gravis
- Phrenic palsy, injury or disease
- Kyphoscoliosis[6]
- Surgery on the right heart
- Total cavopulmonary connection
- Fontan procedure
- Tetralogy of Fallot
- Diaphragmatic palsy.

Non-invasive ventilation can be applied in two ways:

1. *Non-invasive negative pressure ventilation* (NINPV): It supports ventilation by exposing chest wall to subatmospheric pressure inspiration, with expiration occurring as pressure around the chest wall is allowed to

return to atmospheric levels. Body ventilators apply negative pressure to the entire body below neck, by using iron lung. Currently, less bulky and more portable devices have been designed to apply negative pressure. These ventilators have so many disadvantages such as an awkwardly large size, positioning of the patient, and an increased likelihood of upper airway obstruction, leading to a gradual decline in use of this method of ventilation. The use of NINPV in acute respiratory failure is unclear. However, patients with neuromuscular diseases, chest wall deformity, central hypoventilation or diaphargmatic paralysis often do benefit from negative pressure ventilation.

2. *Non-invasive positive pressure ventilation* (NIPPV):[1,2] Non-invasive positive pressure ventilation refers to delivery of positive pressure ventilation to lungs without an invasive airway. The rationale for use of NIPPV is avoidance of endotracheal intubation and its complications. The use of NIPPV has gained increasingly widespread acceptance, for both acute and chronic respiratory failure after the use of nasal or face mask especially in pediatric patients.[3,7]

   Non-invasive positive pressure ventilation[1,4] can be given by:
   - Volume ventilator
   - Pressure controlled ventilator
   - Pressure support ventilation
   - Bi-level positive airway pressure ventilator
   - Continuous positive airway pressure devices.

Volume Ventilation

Volume cycled non-invasive ventilation in which the ventilator delivers a set tidal volume for each breath can improve outcomes in acute respiratory failure and has been used to manage chronic respiratory failure.

However, patient tolerance is often poor, as inspiratory pressures may be too high, which can be uncomfortable and can cause leaks. In these ventilators tidal volume is fixed, inflation pressure may vary.

Tidal volume can be increased to 20-25 ml / kg as this is an open system, but should always be titrated. The assist control mode ensures that tidal breaths are triggered or improved depending on magnitude of inspiratory effort. These modes are preferred non-invasively in patients with neuromuscular diseases who need high tidal volume for ventilation. Leaks are more common with volume mode.

Pressure Control Ventilation[1,4]

Positive pressure non-invasive ventilation in which the ventilator delivers a set pressure for each breath, is commonly given with bilevel positive airway pressure (BIPAP) ventilators or with standard ventilators that use pressure support or pressure control.

In these modes, flow will vary according to patient demands. The ventilator maintains a preset pressure and flow will vary according to resistance. In this mode, tidal volume may decrease when there is no spontaneous inspiratory effort or it is just adequate to trigger ventilator. The respiratory rate and I:E ratio can be set on the device.

Pressure Support Ventilation[1,4]

It is the most popular mode used for non-invasive mechanical ventilation. The ventilator is triggered by the patient and when there is fall in inspiratory flow below threshold preset on the ventilator, the ventilator cycles to expiration. Presssure support is commonly given with Bilevel PAP ventilators. Administering ventilation through a nasal or face mask and standard ventilator allows physician to set inspired oxygen concentration, prevent rebreathing of exhaled gas and use the ventilator alarms and monitors. The pressure support mode delivers the flow when ventilator senses a patient initiated breath and terminates the higher pressure when it detects a fall in flow rate below a threshold value or after a prolonged period.[1]

It is usually well-tolerated by patients, however, there can be problems if air leak is present. The problem can be tackled by using pressure control ventilation, which sets a fixed inspiratory time and provides a backup rate.

Bi-level Positive Airway Pressure Ventilator (BIPAP)[1,3,20]

Bi-level PAP ventilators provide continuous high flow PAP that cycles between a high positive pressure and a lower positive pressure. These devices are sensitive and can detect inspiratory efforts even in presence of leak in circuit. In spontaneous mode, Bilevel PAP responds to patient's own flow rates and cycles between higher pressure and lower pressure. It is essentially similar to pressure support ventilation in concept.

Continuous Positive Airway Pressure (CPAP)

It is applied when the patient is breathing spontaneously. It can be applied by nasal prongs or nasopharyngeal prongs. Nasal prongs constitute a simple system for application of CPAP. Mouth leak provides pressure pop-off but introduces variation in level of CPAP. This system requires high flow of oxygen. Nasopharyngeal prongs are like endotracheal tube inserted through nose to hypopharynx. The length and diameter of any long prong in CPAP system increases resistance and work of breathing. It is very useful in postoperative high risk patient with severe nonhypercapnic oxygenation failure and avoids reintubation.[5,8]

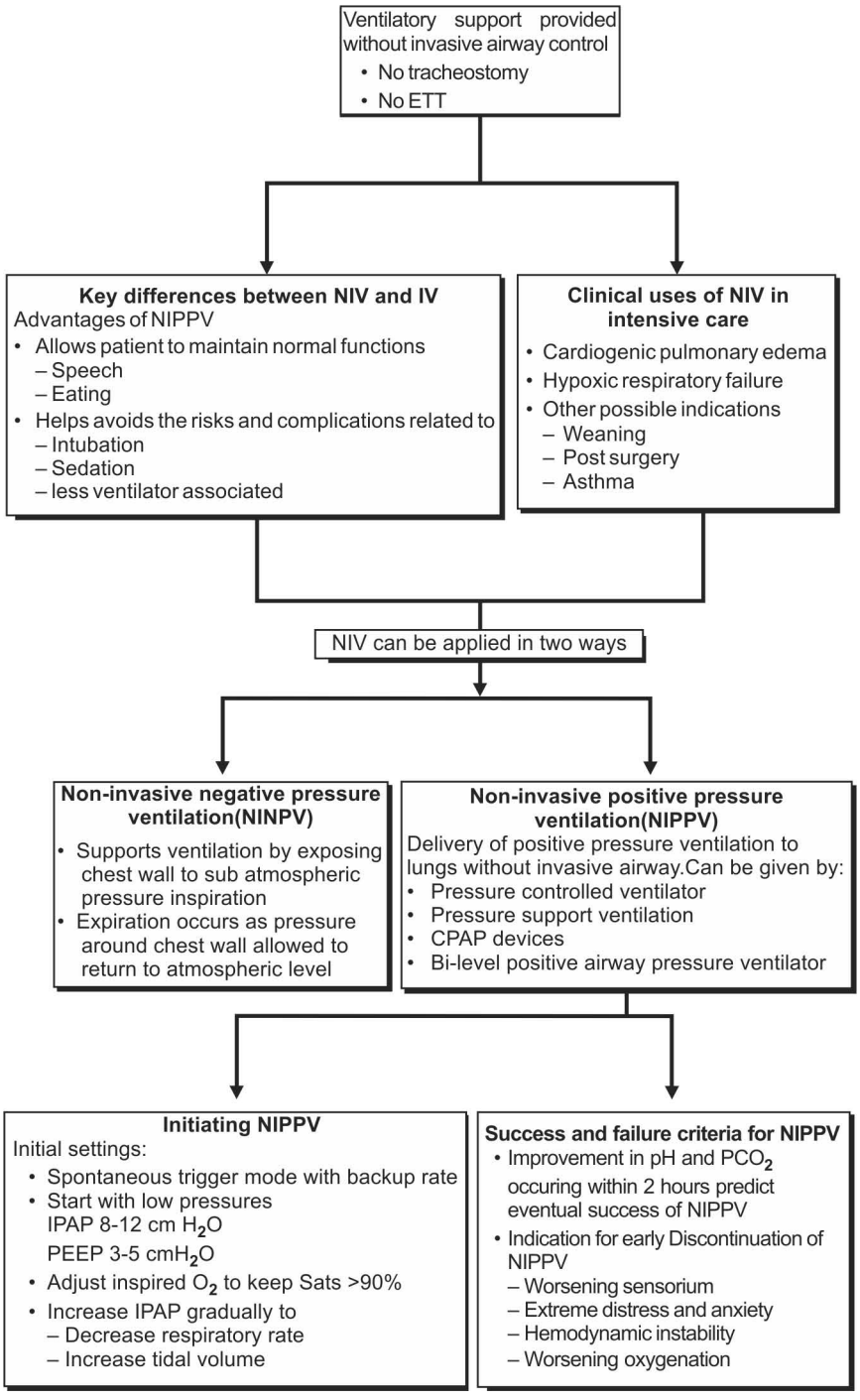
Practical Applications of Noninvasive Positive Pressure Ventilation (Flow chart 14.1)

Chronic Respiratory Failure

NIPPV is commonly used at night for management of chronic respiratory failure. It has proven to be useful in long-term management of neuromuscular disease.

NIPPV during sleep significantly improves day time arterial blood gases, lung volumes and respiratory muscle strength and reduces the number of admissions of patients with severe kyphoscoliosis.[9]

Flow chart 14.1: Non-invasive ventilation



It can be used as maintenance therapy in patients with intrinsic lung disease and marked hypercapnia. Non-invasive ventilation can be helpful in some patients with intractable dyspnea.

Acute Respiratory Failure

NIPPV is an effective means of treating patients with acute respiratory failure due to variety of causes.

Uncontrolled studies using historical controls and prospective randomized studies have shown consistently good results.[9]

Non-invasive ventilation has been successfully used in patient with cystic fibrosis. In pediatric patients with respiratory insufficiency, but without multiple organ system failure, the use of bilevel positive airway pressure support can decrease the need for placement of an artificial airway.[1,10-12]

Non-invasive ventilation can be effectively used in acute respiratory failure due to pneumonia, exacerbation of reactive airway disease, broncho-pulmonary dyspasia, asthma, postoperative hypoventilation with atelectasis, sleep aggravated breathing disorders, patient who are not candidates for intubation.[13-19]

Initiation of Non-invasive Mechanical Ventilation

NIPPV can be given both by conventional ventilators (Figs 14.1A and B) available in pediatric ICU or by specific bilevel positive pressure support ventilation device, which will be discussed here.

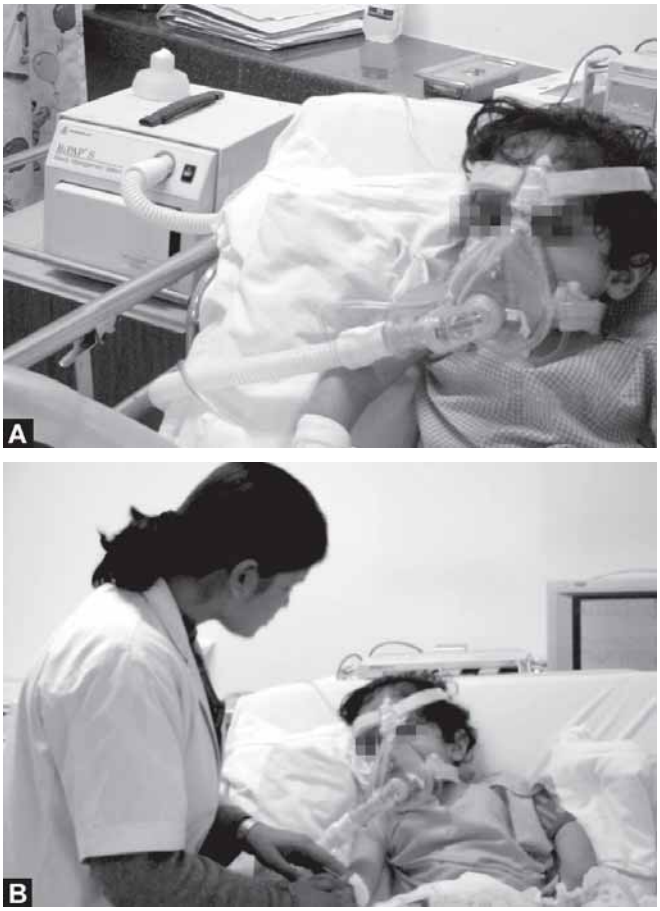
Initially, the mask is gently positioned over the nasal bridge with minimal flow. The initial settings are inspiratory positive pressure of 4 to 5 cm of H_2O and expiratory positive pressure 2 to 3 cm of H_2O.

Inspiratory positive airway pressure is followed by expiratory positive airway pressure. As the delivered pressures are increased, the patient's breathing pattern is observed for chest excursions and breath sound are auscultated for increase in ventilation. Pressures are adjusted to maximize patient comfort level and stability in pattern of oxygenation. Supplemental oxygen can be given via a connecting tube attached to face or nasal mask (Fig. 14.2).

If oxygenation needs are a major concern, expiratory positive airway pressure is optimized. If ventilation is needed to be enhanced as judged by increased $PaCO_2$, the pressure differential between inspiratory positive airway pressure and expiratory positive airway pressure is adjusted because a wider pressure gradient enhances ventilation.

Patient comfort should be always kept in mind and mask should not be too tight to cause discomfort. Small amount of air leak is acceptable. Non-invasive ventilation works best if the patient is relaxed and is less effective if the patient is anxious, uncooperative or fighting with the ventilator. Preparation of patient is critical. In non-emergency situations, the first few sessions can be used simply to fit the mask and familiarize the patient with the apparatus. Different types of modes used for NIV are:

- NIV via nasal mask (Fig. 14.2)
- NIV via double nasal tube (Figs 14.3A and B)



Figs 14.1A and B: Patient on NIPPV (BIPAP on respironics NIPPV ventilator)
(For color version see Plate 2)

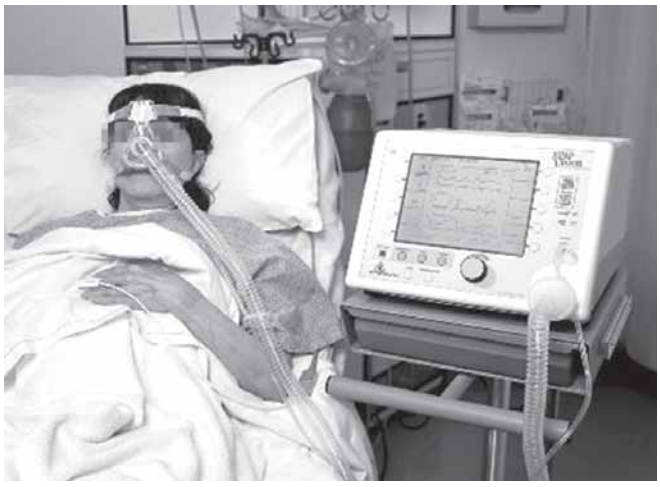
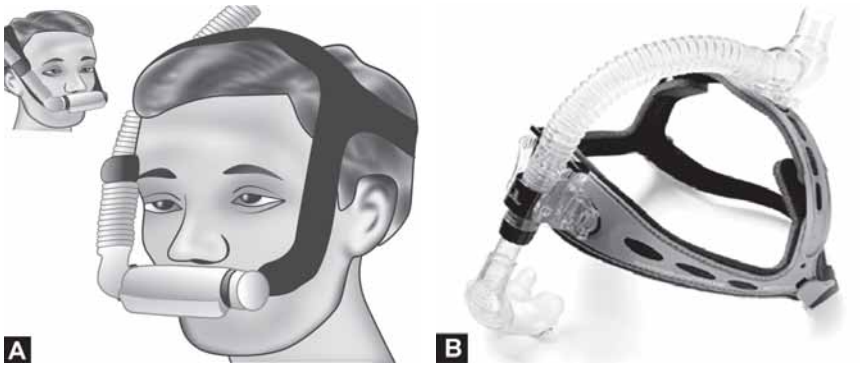
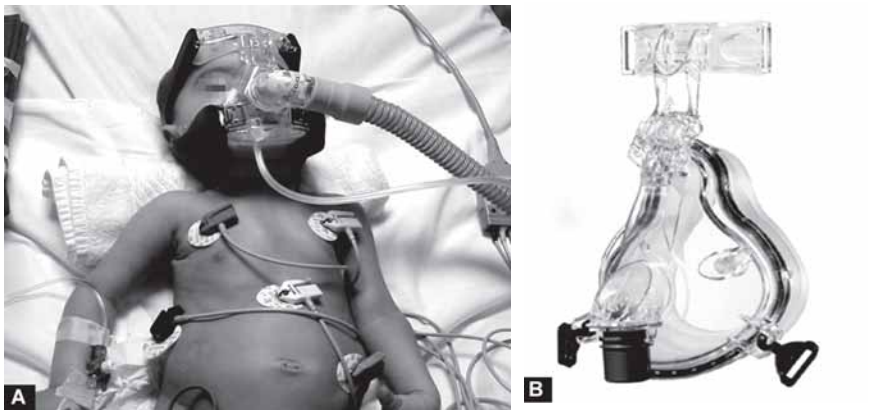


Fig. 14.2: NIV via nasal mask



Figs 14.3A and B: (A) NIV via double nasal tube. (B) NIV double nasal tube



Figs 14.4A and B: (A) NIV via facial mask (B) NIV facial mask

- NIV via facial mask (Figs 14.4A and B)
- NIV via tracheostomy (Fig. 14.5).

Table 14.1 gives information on advantages and disadvantages of different types of masks used for NIV.

Limitations of NIPPV

When NIPPV is applied, patient must be monitored and attention given to their comfort, level of dyspnea, respiratory rate and oxygen saturation. Patients must be watched for signs of ventilator, patient asynchrony, nasal mask intolerance, serious air leaks, gastric distention, drying of the eyes and facial skin breakdown, especially at the bridge of the nose. For a variety of reasons, NIPPV techniques are not always successful. Hemodynamic instability, deteriorating mental status and increasing respiratory rate indicate failure. In general, noninvasive ventilation should not be used in patients who are unable to cooperate or who have impaired consciousness, problems with retained secretions or hemodynamic instability.

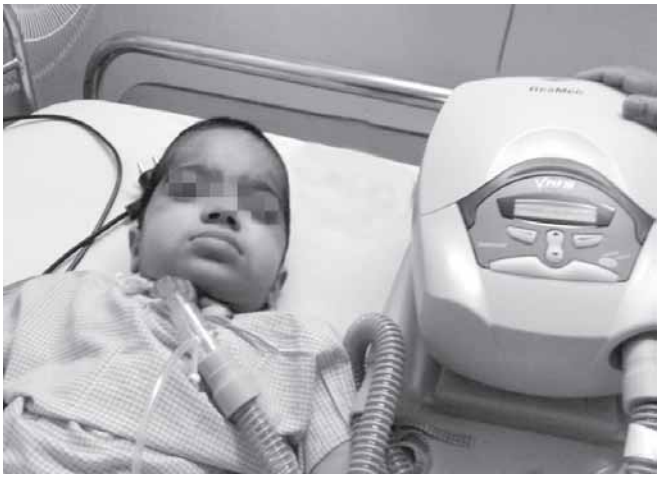


Fig. 14.5: NIV via tracheostomy

TABLE 14.1: Advantages and disadvantages of different types of mask

Types of mask	*Advantages*	*Disadvantages*
Facial mask	Better ventilation Less leakage Skin lesion	Claustrophobia Speaking is not possible Gastric insufflation
Nasal mask	Feeding and speaking Easy to Adjust	Less efficient Leakage through mouth
Double nasal tube	Less pressure on skin No claustrophobia	Difficult to adjust Leakage through mouth

Monitoring during NIPPV[1,3,4,20]

Efficacy of NIPPV is determined by observing the effect on heart rate, respiratory rate, oxygen saturation, oxygen requirement and arterial blood gases. Subjective variables include patient's work of breathing and dyspnea score. There should be regular monitoring of mask fit, comfort, air leak, secretions and skin necrosis. Proper monitoring is very important for NIPPV to be successful after its application (Figs 14.1A and B).

1. *Patient comfort:* The smooth adaptation to the ventilator by the patient is the key to success. If the patient is complaining of discomfort, one should try to make him / her comfortable either by proper fitting of mask or changing interface. One should not force patient to use device against their will.[1]

2. *Vital signs:* Monitoring of vital signs like heart rate, respiratory rate, blood pressure and use of accessary muscle especially sternocleiodo-mastoid muscle. Dyspnea, mental status, complications like abdominal distention, pressure necrosis and the retention of secretions. Try to get

patient to relax as much as explaining him so that he can synchronize well with ventilator and unload his work of breathing.

3. Continuous pulse oximetry.
4. Arterial blood gas.

Blood gas should be done within one hour of initiation of ventilation to adjust ventilatory settings and later at 2 to 6 hour interval.

Patient need not to be sedated. Relief of dyspnea and respiratory distress are achieved but correction of acidosis may be slower. Patients showing improved gas exchange within one hour of initiation of ventilation are less likely to get intubated.

The first 30 minutes of NIPPV are laborious and intensive. Providing reassurance and adequate explanation is very important. Patient or the parent may be instructed to call if the child needs any help, like removal or repositioning of mask, for oral intake or expectoration of secretions.

Indication for early discontinuation of NIPPV:[3]

- Worsening level of sensorium
- Extreme distress and anxiety
- Inability to clear secretions
- Hemodynamic instability
- Worsening oxygenation to inability to maintain saturation
- Inability to tolerate mask due to discomfort / pain.

Weaning

Once the primary cause has been reversed and patient is better, weaning should be tried. Intermittent weaning can be done by removal of mask initially for few hours and if patient tolerates it well, one can gradually increase the period and then discontinue. Initially weaning should be done during day time and continued during the night for first 1 to 2 days. If patient tolerates it well, NIPPV can be discontinued. ABG must be done to assess success of weaning regularly.

Complications of NIPPV

NIV complications are related to the mode of ventilation.

Collapse of upper airway is the main problem encountered with the *negative-pressure extrathoracic ventilation* and is more frequent with overweight patients. Other complications like pain, esophagitis, rib fractures or pneumothorax are linked to the cuirass itself.

Bruises and Erosions

Problems linked to NIPPV are related to the interface between the patient and the ventilator. Skin bruises on the nasal bridge or the chin or on the flares with nasal canulae can be minimized when the adequate size and type of interface is selected and with placement of comfeel or duoderm between the skin and the interface. Pediatric studies report a complication rate of 7 to 12 percent, mainly facial skin necrosis.

More serious complications like barotrauma or aspiration pneumonia are related to NIV in less than one percent of patients.[12] Other complications described in children are gastric distention (with IPAP of more than 25 cm H_2O and above the opening pressure of the low esophageal sphincter), non-fitting mask, intolerance and bad adaptation of the child to the interface.

Contraindications to NIPPV include hemodynamic instability, loss of airway protective mechanisms, loss of consciousness, and very thick oral or tracheal secretions.

CONCLUSIONS

NIPPV can be safely administered outside the pediatric ICU or at home if required for long-term nocturnal support for sleep related breathing disorders. NIPPV is of potential benefit in acutely critically-ill pediatric patients with acute respiratory distress as a means of avoiding intubation. NIPPV should be considered in patients clinically judged to be in early acute respiratory distress and who would otherwise require an artificial airway for respiratory support. NIPPV can result in decrease in heart rate, respiratory rate and dyspnea scores and improvement in gas exchange can occur in patient with underlying neuromuscular diagnosis or patients with chronic lung disease with acute exacerbation. Proper patient selection is essential. Experienced staff must be available and surveillance must be maintained closely to avoid dangerous delays if intubation is necessary. Effective NIPPV reduces the duration of ventilatory support and its associated complications. Mortality from acute respiratory failure may also be decreased when endotracheal intubation is avoided. For these reasons pediatric intensivist should become familiar with this modality and consider its implementation for eligible patient group (Flow chart 14.1).

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15 Chapter

Neonatal CPAP (Continuous Positive Airway Pressure)

Praveen Khilnani

DEFINITION

A technique of airway management in which Positive intrapulmonary pressure is applied artificially to the airways , whereby distending pressure is created in the alveoli in a spontaneously breathing baby throughout the respiratory cycle.

Harrison, first increased alveolar pressure during expiration in RDS leading to abolition of the grunt in RDS deterioration.

Gregory et al (1971) used CPAP first in **spontaneously** breathing neonate in RDS.

The advent of less invasive methods of delivering CPAP has permitted earlier treatment of infants with respiratory distress syndrome (RDS) and avoided the need for mechanical ventilation. The early initiation of nasal CPAP in combination with a tolerance to elevated PCO_2 levels has reduced the incidence of BPD in many centers.

EFFECTS OF CPAP IN THE INFANT WITH RESPIRATORY DISTRESS

1. Reduces upper airway occlusion by decreasing upper airway resistance and increasing the pharyngeal cross sectional area.
2. Reduces right to left shunting.
3. Reduces obstructive apneas.
4. Increases the functional residual capacity (FRC).
5. Reduces inspiratory resistance by dilating the airways. This permits a larger tidal volume for a given pressure, reducing the work of breathing.
6. Increases the compliance and tidal volume of stiff lungs with a low FRC by stabilizing the chest wall and counteracting the paradoxical movements.
7. Regularizes and reduces the respiratory rate.
8. Increases the mean airway pressure and improves ventilation perfusion mismatch.
9. Conserves surfactant on the alveolar surface.
10. Diminishes alveolar edema.
11. Nasal CPAP after extubation reduces the proportion of babies requiring reventilation.

12. Oxygenation is related to the surface area, and carbon dioxide elimination is related to the minute volume. Normalizing lung volume improves oxygenation and carbon dioxide elimination.

Indications for CPAP

1. Spontaneously breathing babies with respiratory distress at birth.
2. Increased work of breathing indicated by: recession, grunting, nasal flaring, increased oxygen requirements or increased respiratory rate.
3. Poorly expanded or infiltrated lung fields on chest X-ray.
4. Atelectasis.
5. Pulmonary edema.
6. Pulmonary hemorrhage.
7. Apnea of prematurity.
8. Recent extubation.
9. Tracheomalacia or other abnormalities of the airways, predisposing to airway collapse.
10. Phrenic nerve palsy.

Contraindications to CPAP

1. The need for ventilation because of ventilatory failure—inability to maintain oxygenation and the arterial $PaCO_2$ < 8 kPa and pH > 7.25.
2. Upper airway abnormalities (cleft palate, choanal atresia).
3. Tracheoesophageal fistula.
4. Diaphragmatic hernia.
5. Severe cardiovascular instability.

THE CPAP DELIVERY SYSTEM

The CPAP delivery system consists of three components: The *circuit* for continuous flow of inspired gases, the *interface* connecting the CPAP circuit to the infant's airway, and a *method of creating positive pressure* in the CPAP circuit (Fig. 15.1). Endotracheal CPAP is usually not recommended, nasal CPAP is preffered.

The magnitude of CPAP may be varied by a change in the *amount of gas flow* into the system or by the *amount of obstruction to the outflow* (5 cm of fluid level in the case of bubble nasal CPAP).

Three Types of CPAP Delivery Systems

1. Ventilator CPAP system (Fig. 15.2)
2. Infant flow driver (Fig. 15.3)
3. Bubble CPAP system (Fig. 15.4)

Various interfaces are also available, such as Argyle, Hudson or Fisher and Paykle nasal prongs (Figs 15.5 to 15.7).

Initiating and Maintaining Optimal NCPAP

- Correctly set up and maintain low resistance delivery circuit
- Securely attach interface

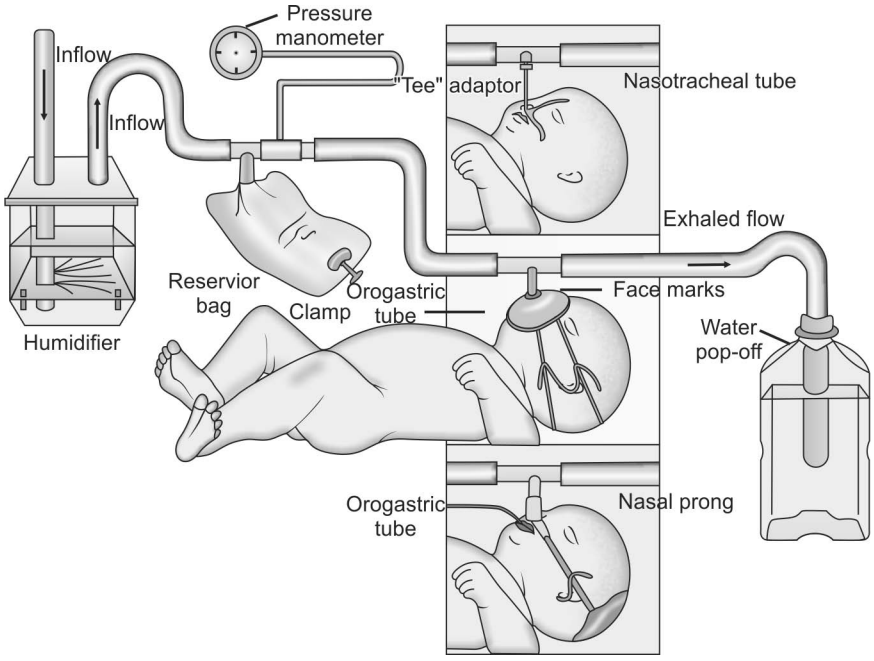

Fig. 15.1: CPAP delivery system

Fig. 15.2: Infant ventilator CPAP system

- Assure minimal pressure leaks
- Maintain optimal airway
- Prevent nasal septal injury
- Provide meticulous attention to details
- Resist the temptation to 'improve' the system
- Encourage committed and skilled caregivers.

Fig. 15.3: Infant flow driver CPAP system

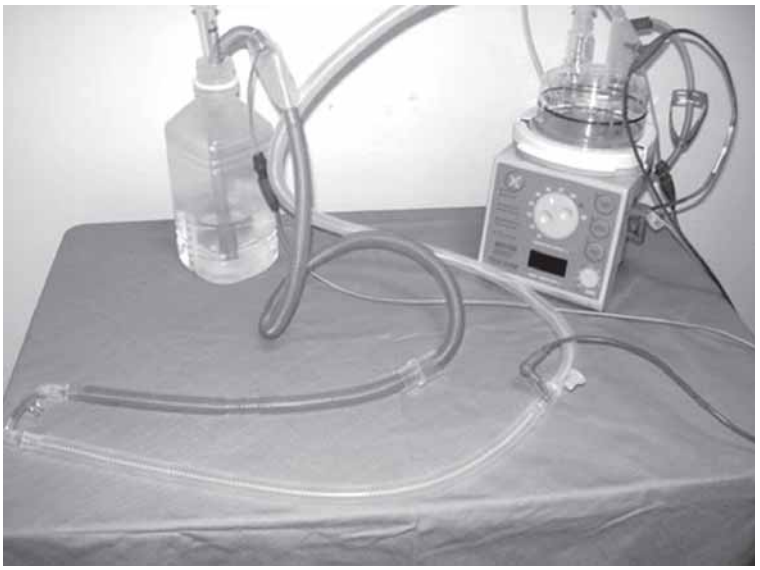

Fig. 15.4: "Bubble" nasal CPAP system

1. *Circuit maintenance*
   - Flow between 5-10 L / m (7-8 L / m)
   - Humidification
   - Corrugated tubing clear of excess rain out
   - 5 cm water pressure
   - Change circuit (less nasal prongs) weekly.
2. *Securely attached interface*
   - Snug fitting hat
   - Snug fitting nasal prongs

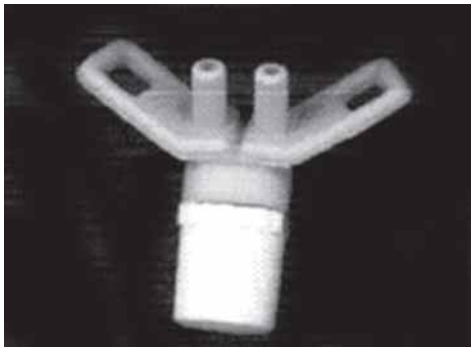

Fig. 15.5: Argyl nasal prongs

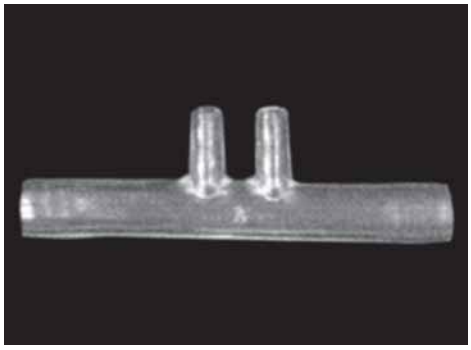

Fig. 15.6: Hudson nasal prong

Hudson nasal prong size

size 0 for < 700 gm
size 1 for 700-1000 gm
size 2 for 1000-2000 gm
size 3 for 2000-3000 gm
size 4 for 3000-4000 gm
size 5 for > 4000 gm

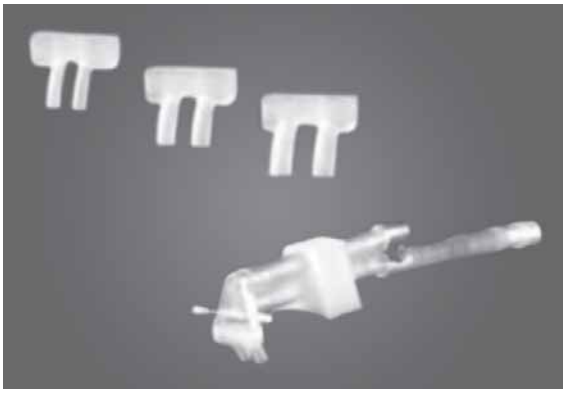

Fig. 15.7: Fisher and Paykle prongs

For infants at the high end of any of the weight ranges, consider using the larger prongs appropriate for the next higher weight range

- Velcro moustache
- Chin strap.

Success with NCPAP

NCPAP is successful when meticulous attention is paid to both the infant and to the NCPAP Delivery System. This involves vigilance in:

- Monitoring the infant's condition
- Maintaining an optimal airway
- Maintaining a patent CPAP delivery circuit
- Prevention of complications which may arise from NCPAP.

Monitoring

- Once NCPAP is applied, the infant's condition must be monitored frequently
- Observe the infant after 1 hour over the first 4 hours of life, and then after 3-4 hours thereafter while on NCPAP
- Any infant experiencing significant respiratory distress while on NCPAP, requires closer observation for change in condition.

Recommended Monitoring

- Respiratory status (RR, work of breathing)
- Pre-ductal oxygen saturation
- Cardiovascular status (HR, BP, perfusion)
- GI status (abdominal distention, bowel sounds)
- Neurological state (tone, activity, responsiveness)
- Thermoregulation (temp).

Suction the mouth, nose and pharynx after 3 hours.

- For symptomatic infants, more frequent suctioning may be needed.

Maintain adequate humidification of the circuit to prevent drying of secretions.

- Adjust settings to maintain gas humidification at or close to 100%
- Set the humidifier temperature to 36.8-37.3° C
- Minimal handling / Sedation
- Nasal prongs of right size in place (fixation)
- Orogastric tube
- Care of the nares
- Change of posture
- Vitals and Continuous pulse oximetry
- Blood gas, hematological, radiological and biochemical monitoring.

Advantages and Disadvantages of Nasal Prongs CPAP

Advantages

Easy to apply; flexible and enable change in infant's position; low airway resistance, easily controlled, stabilized and eliminates need for intubation.

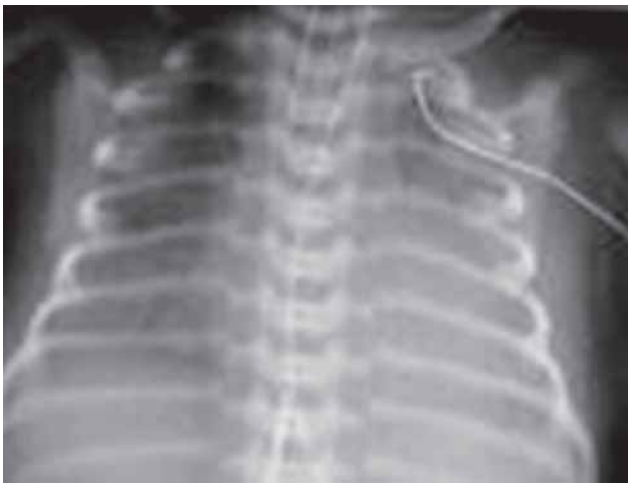

Fig. 15.8: Severe RDS

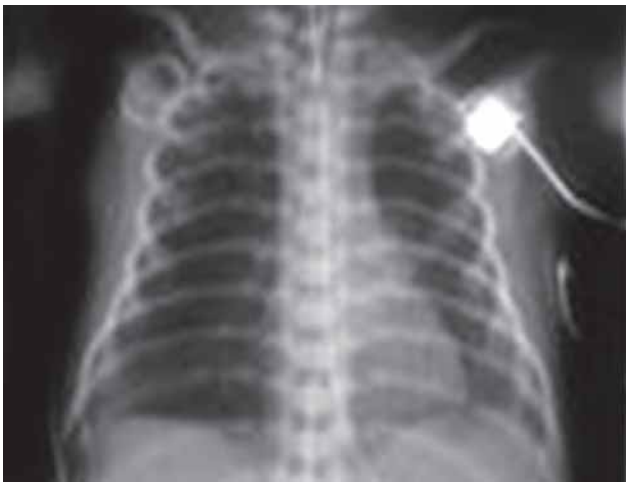

Fig. 15.9: Improved RDS with CPAP

Disadvantages

Nasal septal erosion or necrosis; nasal obstruction from secretions or improper position of CPAP prongs; abdominal distention from swallowing air.

Conditions when CPAP Fails

- Recurrent apneic attacks
- Spontaneous episodes of desaturation
- Increasing oxygen requirements
- Worsening respiratory distress
- Agitation not relieved by simple measures
- Worsening blood gases.

Figures 15.8 and 15.9 show radiological improvement after 3 days of CPAP in premature RDS.

Complications Associated with Bubble Nasal CPAP

One needs to be aware of the associated complications and possible prevention.

Pneumothorax/Pulmonary Interstitial Emphysema (PIE)

Seen more in the acute phase and PIE is not a contraindication for continuing CPAP. Pneumothorax is usually not due to NCPAP.

Nasal Obstruction

Remove secretions and check for proper positioning of the prongs.

Preventing Injury to Nasal Septum

- Evaluate the nasal septum after 30-60 minutes
- Use correct prong size
- Secure prongs in place correctly
- Use Velcro moustache
- Maintain distance of 2-3 mm between bridge of prongs and septum
- Avoid twisting of prongs
- Do not use creams, gels, ointments or adhesive barriers (Duoderm) on the septum.

To Prevent Gastric Distention

- Assess the infant's abdomen regularly
- Pass an orogastric tube to aspirate excess air before feeds after 2-4 hours
- An 8 Fr orogastric tube may be left indwelling to allow for continuous air removal.

If an Infant Develops Symptoms of Respiratory Failure on NCPAP then One or More of the following may apply

- The infant is not receiving effective CPAP
- CPAP is not sufficient to treat the infant's respiratory disease
- An underlying condition is contributing to the infant's respiratory failure.

Respiratory Failure on CPAP

1. Symptoms:
   - Significant apnea
   - Respiratory failure (PCO_2 > 65 mm Hg)
   - Progressive hypoxemia
   - Severe respiratory distress.
2. Procedures prior to intubation:
   - Evaluate the infant's clinical condition: Is the clinical condition compatible with the blood gas evaluation?
   - Check the NCPAP delivery system for proper functioning: Is the system bubbling properly? Are air leaks by mouth and nose minimized?

- Suction the infant and reposition the nasal prongs: Are the nares obstructed? Are the prongs of the correct size and position?
- Increase the CPAP to 7 cm H_20: Does the infant respond to higher pressure?

If the infant continues to show evidence of respiratory failure ..... then, intubate.

When to Wean NCPAP?

If less than 7 days old, must meet all of the following criteria:

- FiO_2: 0.21
- Oxygen saturations > 90%
- No respiratory distress (Infant has no evidence of tachypnea or retractions)
- No significant apnea / bradycardia episodes.

If more than 7 days old, then:

- The decision is usually at discretion of the neonatal team based on clinical condition.

Procedures for Removal of NCPAP

The infant's nose and mouth should be suctioned thoroughly prior to, and after removal of NCPAP.

Cycle off (e.g. 1 hour off, 2 hours on, increase time off progressively) (no evidence).

The infant is carefully monitored after removal of the NCPAP for evidence of tachypnea, retractions, or increased apnea and bradycardia.

The infant is suctioned every 6 hours for the first 24 hours after the removal of NCPAP.

Indications for Reintroducing NCPAP

If the infant develops frequent apnea and bradycardia episodes, tachypnea or retractions, the nasal CPAP is reintroduced.

Evidence for CPAP

Some studies are quoted in the following discussion looking at the clinical evidence supporting the use of CPAP in neonates.

Early Bubble CPAP and Outcomes in ELBW Preterm Infants

Non-randomized study using historical controls Narendran et al. *J Perinatol* 2003 Period 1 (1998-99): CPAP was not used in the DR; early intubation and surfactant administration (n = 92) Period 2 (2000-1): routine, early bubble CPAP in the DR (n = 79). Elective intubation and Survanta – Aggressive extubation back to bubble CPAP.

Results: Introduction of early bubble CPAP reduced DR intubations, days on MV, postnatal steroid use; increased mean days on CPAP; CLD 40% vs 34% p = NS.

Prophylactic CPAP in VLBW Infants

Subramaniam P, Cochrane 2005

- No reduction in BPD
- Trend towards increased incidence of IVH
- Therefore, as of now prophylactic CPAP is not recommended especially in infants ≥ 28 weeks gestation.

Other Studies

CPAP helps preterm infants Level Of Evidence(LOE 4)
Linder et al. *Pediatrics*. 1999;103:961

No difference in outcomes (LOE 2)
Finer et al. *Pediatrics*. 2004;114:651

Excessive CPAP detrimental (LOE 6)
Heulitt et al. *Respir Care*. 2003;48:689
Furzan et al. *Pediatr Res*. 1981;15:874

Insure Approach

In infants with signs of RDS, intubation and surfactant therapy followed by extubation to NCPAP compared with later selective surfactant administration was associated with lower incidence of mechanical ventilation (RR 0.70, 0.59 to 0.84) and increased surfactant use.

It is uncertain if BPD is reduced by this approach. *Cochrane, 2004*

Does CPAP facilitate weaning of premature infants from mechanical ventilation?

Extubation After Trial of ET CPAP: 3 clinical trials (Kim and Boutwell 1987; Kim 1989; Tapia 1995)

- ET CPAP (2-4 cm H_2O) prior to extubation confers no advantage over direct extubation
- Successful extubation is more likely in infants extubated directly to headbox or nasal prong CPAP from low-rate IPPV
- ET CPAP was associated with a trend towards increased frequency of apnea
- ET CPAP is more strongly associated with adverse outcomes in smaller infants (with smaller ET tubes).

CONCLUSION

- Early use in RDS babies between 1-1.5 kg is often rewarding
- Trial of CPAP for bigger babies > 1.5 kg is often successful, thus, avoiding IMV
- Useful after extubation for < 1.5 kg.
- Excellent modality for management of apnea of prematurity.

SUMMARY

CPAP is a commonly used modality in neonatal units for mainly premature lungs for RDS with or without the use of surfactant (and few term babies

with respiratory distress) and the success depends on proper patient selection, full team support in initiation, monitoring and discontinuation.

Mechanical ventilation facility must remain available in the neonatal units in case of failure of NCPAP. If intubation is required, ET ventilation should be delivered and ET CPAP should be discouraged in view of increased airway resistance.

Complications can be prevented if adequate precautions are taken.

16

Chapter

Neonatal Ventilation

Anjali A Kulkarni

Respiratory distress is one of the commonest causes of mortality and morbidity in the neonatal period. Fortunately, most of the conditions leading to respiratory failure in the newborn are reversible and complete recovery can be achieved with prompt management. Thus, adequate support of respiration is integral to the care of the sick newborn and the advent of assisted ventilation has made this possible.

Definition

Assisted ventilation is defined as the movement of gas into and out of lung by an external source connected directly to the patient.[1]

In the neonate, assisted ventilation is usually a temporary measure for supporting pulmonary function until the patient can breathe adequately without help. The purpose of ventilation is to provide adequate oxygen, remove carbon dioxide and reduce the work of breathing. This is accomplished through the use of a device that augments or replaces the bellows action of the respiratory musculature.

Beneficial effects of ventilatory therapy are dependent on a strong knowledge of this subject, skill and experience in management combined with constant vigilance by medical, nursing and respiratory personnel during treatment.

Until the 1970's ventilators used in Neonatal Intensive Care Units (NICU) were modifications of adult devices. From 1971-1995 myriad of new ventilators specifically designed for neonates were manufactured and used. The first generation ventilators included the BABY bird 1, the Bournes BP 200 and a volume ventilator, Bournes LS 104/50. All operated on the intermittent mandatory ventilation (IMV) principle.

Subsequently, second and third generation ventilators have allowed new dimensions in neonatal assisted ventilation. This combined with development of surfactant replacement therapy has revolutionized the management of acute respiratory distress in the newborn. However, the goal of the future is the application of effective therapy without iotrogenic consequences.

It is not possible to cover the details of various ventilatory techniques however, some of the common methods, their indications, contraindications and long-term effects are described in this chapter.

TABLE 16.1: Causes of respiratory failure

Problem area	*Possible causes*
Pulmonary	RDS, Aspiration syndromes, Pneumonia, Pulmonary Hemorrhage, Wilson-Mikity syndrome, Bronchopulmonary dysplasia, Insufficiency of prematurity, Pneumothorax, Tumor, Diaphragmatic hernia, Chylothorax, Congenital malformation
Airway	Laryngomalacia, Choanal Atresia, Pierre Robin syndrome, Micrognathia, Nasopharyngeal tumor, Subglottic stenosis
Abnormalities of muscles of respiration	Phrenic nerve palsy, Spinal cord injury, Myasthenia gravis, Werdnig-hoffmann syndrome
Central problems	Apnea of prematurity Drugs: Morphine, magnesium sulfate, mepivacaine, meperidine, Seizures Birth asphyxia, Hypoxic encephalopathy, Intracranial hemorrhage, Ondines curse, Rapid eye movement sleep
Miscellaneous	Congestive heart failure, Persistent fetal circulation, Postoperative anesthesia/Sedation, Tetanus neonatorum, Extreme immaturity, Shock, Sepsis, Hypoglycemia, Electrolyte abnormalities, Acid-base imbalance, Infant botulism Hydrops fetalis

Initiation of Ventilation

The commonest indication for neonatal ventilation is respiratory failure. The causes of neonatal respiratory failure are depicted in Table 16.1.

These can be roughly divided into two types. One where lungs are normal but patient fails to breathe, i.e. apnea and second where mechanism of pulmonary gas exchange is compromised due to lung disease.

It is important to make distinction between two types of lung diseases—atelectatic and obstructive. This distinction is important as it helps the clinician to address the criteria for initiation of ventilation, the choice of ventilator and the parameters of ventilator control. The specific objectives to achieve and complications to avoid in assisted ventilation of the newborn are given in Table 16.2.

The diagnosis of respiratory failure is based on clinical findings and results of acid-base analysis.

1. Clinical manifestations:
   - Increasing respiratory rate
   - Increasing respiratory effort / retractions
   - Prolonged apnea, cyanosis not relieved by oxygen administration
   - Gasping and use of accessory muscles of respiration

   Silverman Anderson score is often helpful in evaluation and score of > 7 indicates impending respiratory failure.
2. Blood gas parameters:
   - $PaO_2 < 50$ mm Hg
   - $PaCO_2 > 60$ mm Hg
   - Ph < 7.25.

TABLE 16.2: Objectives of ventilation

Objectives to achieve	*Complications to avoid*
Maintain desired level of PaO_2 or SaO_2	Avoid O_2 toxicity to the lungs, broncho-pulmonary dysplasia, Retinopathy of prematurity, Hypoxemia pulmonary vasoconstriction or tissue damage
Maintain desired level of $PaCO_2$ optimum level of alveolar ventilation	Avoid Hyperventilation causing cerebral ischemia
Reduce work of breathing and respiratory muscle fatigue	Avoid alveolar overdistention, wasted ventilation, rupture and pulmonary air leak Suppression of ventilatory drive Increased upper airway resistance
Re-expand atelectatic or collapsed alveoli and lung segments	Hyperinflation/overexpansion of areas already inflated Pulmonary hypoperfusion, Reduced venous return and cardiac output

Basic Principles of Ventilation

According to classic theory, ventilation involves the movement of gas by convection or bulk flow through the conducting airways and then by molecular diffusion into the alveoli and pulmonary capillaries. The driving force for convection is the difference in pressure at origin and distention of the flowing gases, for diffusion it is the difference in the concentration of the intermingling gases in the adjacent spaces.

The amount of gas drawn in through the nose on delivered breath during a single cycle of ventilation is called tidal volume (VT). VT in milliliters multiplied by the number of breaths per minute or respiratory frequency defines minute ventilation (VE).

$$VE = VT \times f$$

The trailing portion of the column of incoming tidal gas never arrives at the alveoli but rather fills the conducting airways. This portion constitutes the anatomic dead space. Another portion of the tidal gas may be delivered to the alveoli but may enter the alveoli that are not perfused. Since gas exchange does not take place in these units, the volume that they constitute is called alveolar dead space. Together they are called total or physiologic dead space (VDS). The ratio of dead space to tidal volume defines wasted ventilation which reflects the proportion of tidal gas delivered that is not involved in actual gas exchange.

Types of Ventilatory Support

Continuous Positive Airway Pressure (CPAP) (also see Chapter 15)

A continuous flow of heated humidified gas is circulated past the infants airway at a set pressure of 3-8 cm of H_2O maintaining an elevated end expiratory lung volume while the infant breathes spontaneously. CPAP is

usually delivered by means of nasal prongs or nasopharyngeal tube. It improves oxygenation by an increase in the functional residual capacity. However, overreliance on CPAP may be dangerous and it should only be used if infants show adequate respiratory effort, appear to be tolerating the procedure well and maintain adequate arterial blood (pCO_2 < 50 mm Hg, pH > 7.25, PaO_2 > 50).

With all CPAP devices some air may get into the gut and cause gastric distention. This can be prevented by using an open ended orogastric tube *in situ*. CPAP effectively splints the chest wall, keeps the airways patent thereby preventing obstructive apnea and atelectasis. Various studies have documented the efficacy of CPAP in respiratory distress of mild to moderate degree.[2] Recently trials have been conducted on using nasal intermittent positive pressure (NIPPV) and it has been found to have similar results as CPAP. Indigenous CPAP systems as well as CPAP machine may be used to deliver CPAP. However, a facility for ventilation should be available in case the patient has deterioration in respiratory status.

Conventional Ventilation

Conventional ventilators can be classified in different ways as given below:

1. By pressure relationship to patient, i.e. positive or negative.
2. By cycling mode (at termination of inspiration).
3. By power source.
4. By rate.

The commonest type of ventilation used for neonates is pressure limited, time cycled ventilation where a peak inspiratory pressure is set and gas is delivered to achieve that target pressure.

After the target is reached, the remainder of the gas volume is released into the atmosphere, as a result *the tidal volume delivery with each breath is variable* despite the recorded peak pressure being constant.

Inspiration also ends after a preset time period.

In contrast, in volume limited modes, a preset volume is delivered with each breath regardless of the pressure that is needed.

Some ventilators also use airway flow as the basis of cycling in which inspiration ends when flow has reached a critical low or preset level (flow cycled ventilation).

In pressure limited, time cycled continuous flow ventilators following parameters are set at the outset:

- Peak inspiratory pressure (PIP)
- Peak end-expiratory pressure (PEEP)
- Inspiratory time (ti)
- Rate.

This system is relatively simple and maintains good control over respiratory pressures.

Disadvantages

- Poorly controlled tidal volume
- Does not respond to changes in respiratory compliance

- Spontaneously breathing infants may receive inadequate ventilation and are at increased risk for air leaks.

Alternative Modes of Ventilation

Due to disadvantages associated with conventional ventilation, the following alternative strategies are being used increasingly:

Patient Triggered Ventilation (PTV)

This is a form of ventilation where machine-delivered breath is initiated in response to a signal derived from the patient's own inspiratory effort, thus synchronizing the onset of both spontaneous and mechanical breaths. The types of signals used to provide PTV to newborn vary and could be impedance, pressure or flow. The basic feature is shifting the control of breathing from clinician to patient and the newer generation of ventilators allow its application to the smallest of babies.[3]

PTV can be of following types:

a. *Assist/control ventilation:* This is the best mode of ventilation in acute phase of illness as it requires least amount of patient effort and produces improved oxygenation at the same or lower mean airway pressure than conventional modes. In this type of ventilation, a positive pressure breath is delivered in response to patient's inspiratory effort (assist) provided it exceeds a preset threshold criteria. There is a back-up rate (control) in case patient stops breathing. The inspiratory flow is proportional to patient effort and ventilation is tolerated well.
b. *Synchronous intermittent mandatory ventilation (SIMV):* In this mode of ventilation, mechanically delivered breaths are cycled at a rate set by the clinician but are synchronized to the onset of the patient's own breath. Patient breathes freely in between the mechanical breaths. This ensures less risk of 'fighting' or airleaks and sedation is not required. SIMV is particularly helpful for weaning from ventilation.[4]
c. *Pressure support ventilation (PSV):* This is similar to assist/control ventilation except that it is flow cycled, thus patient has full control over how much to breathe and for how long (ti). Although, PSV can be used for full ventilation (PSV max), in practice it is generally used as a weaning mode.
d. *Proportional assist ventilation (PAV).*
e. *Mandatory minute ventilation (MMV).*

There are other promising ventilatory strategies currently under development for clinical use but no data is available relating to their use in neonates.

Rescue Strategies for Management of Ventilatory Failure

Despite improved ventilatory technique, conventional ventilation may fail in certain situations. A commonly used parameter to assess the efficacy of ventilation is oxygenation index (OI).

$$OI = P_{AW} \times FiO_2 \times 100\ PaO_2$$

P_{AW} = Mean airway pressure
FiO_2 = Concentration of inspired oxygen
PaO_2 = Partial pressure of oxygen

OI of 25-40 indicates insufficient ventilation with existing mode of support.

OI of > 40 indicates respiratory failure.

Various rescue therapies, as given below, are currently practiced.

High Frequency Ventilation

This can be of two types–High Frequency Oscillatory Ventilation (HFOV) and High Frequency Jet Ventilation (HFJV) (see chapter on High Frequency Ventilation).

In newborns, high frequency oscillation has been found to be effective in certain situations. During this type of ventilation, a continuous flow of fresh gas rushes past the source that generates the oscillation and a controlled leak or low pass filter allows the gas to exit the system. Both inspiration and expiration are active processes. Oscillations are generated at a frequency ranging from 3 Hz-15 Hz [1 hertz (Hz) = 60 breaths] per minute. Pressure oscillations within the airway produce tiny tidal volume fluctuations around a constant distending pressure. The amplitude of the pressure, which varies from 15-50 cm H_2O, determines the tidal volume. This ventilation causes uniform recruitment of alveoli and there is significantly lower risk of air leaks.

Earlier studies on HFOV had raised some doubts about the risk of IVH, however randomized controlled trials carried out with proper selection criteria have depicted a significantly better outcome with HFOV in certain conditions.[5] This mode of ventilation has been found to be effective in respiratory distress complicated by PPHN (primary pulmonary hypertension).[6] Only Sensorimedics 3100/3100A, a high frequency oscillator has been approved by FDA for early intervention (prophylactic HFOV) but it is not commonly preferred form of therapy.

High Frequency Jet Ventilation is a variant of HFOV and the differences are tabulated in Table 16.3.

Inhaled Nitric Oxide (INO)

(Please Refer to Chapter on Nitric Oxide).

Nitric oxide (NO) appears to be ubiquitously distributed within universe. Critical care physicians have been most interested in the profound regulatory effects of NO on vascular tone. Inhaled nitric oxide distributes only to aerated lung where it rapidly diffuses from endothelial cells into subjacent vascular smooth muscle cells and stimulates Guanylate Cyclase to increase the concentration of Cyclic Guanosine Monophosphate (GMP) that in turn causes smooth muscle relaxation. This localized vasodilator effect improves V/Q mismatch. NO that diffuses into vascular space is

TABLE 16.3: Differences in high frequency jet ventilation (HFJV) and high frequency oscillatory ventilation (HFOV)

	HFJV	*HFOV*
Rate (Hz)	1.5-3.00	3.00-15
Expiration	PASSIVE	ACTIVE
Special ETT (reintubation)	YES	NO
Gas Exchange	++	++
$PaCO_2$ reduction	++	++
PaO_2 increase	+ –	+
Cardiac output	+ –	–
Tracheal injury	++	?

quickly converted to methemoglobin, thereby avoiding systemic vasodilator effect. Inhaled nitric oxide is particularly useful for treating persistent pulmonary hypertension complicating RDS.[7] This can be used with both conventional and high frequency ventilation. Kinsella et al have reported outcome in nine cases of PPHN treated with INO. Within 15 minutes of initiation, PaO_2 increased from 55 mm Hg to 136 mm Hg and OI reduced from 60 to 26.[8] The first three had to be shifted to ECMO but the remaining six recovered completely.

Patients with pulmonary hypertension secondary to congenital heart disease may also benefit both diagnostically and therapeutically from NO. Sometimes, NO may combine with O_2 to form NO_2 and peroxynitrite, which could be highly toxic to the body. Thus, further studies are required to confirm the short-term and long-term safety of INO usage in very young infants. The dose range used (10-80 parts per million) also needs to be standardized, lower end of dose (10-20 ppm) seems to be as effective. It is a prohibitively expensive therapy.

Extracorporeal Membrane Oxygenation (ECMO)

This is a life-support technique used for profound cardiorespiratory failure in infants who fail to respond to conventional therapy.[9] The need for ECMO has declined after the arrival of HFOV and INO for treatment of persistent pulmonary hypertension.

Method

Extracorporeal life-support is provided by draining blood from venous circulation, adding oxygen, removing carbon dioxide via membrane oxygenator (artificial lung). Blood is returned to either the venous or arterial circulation. ECMO allows "lung rest" and lungs are protected from further injury due to barotrauma or oxygen since lower ventilatory settings can be used.

Indications

1. Reversible respiratory failure.
2. Predicted mortality rate with conventional therapy great enough to warrant the risk of ECMO.
3. Oxygenation index of greater than 40 with 2 hours of conventional ventilation. This treatment is available at few centers across the globe.

Contraindications

Absolute

1. Greater than grade III IVH.
2. Two or more weeks of mechanical ventilation.

Relative

1. Greater than grade II IVH.
2. Birth weight < 2 kg or gestation < 34 weeks.
3. Mechanical ventilation for more than 10 days.

Liquid Ventilation (LV)

The principle behind LV is based on laplace equation, i.e. $P = 2T / r$

P — Distending alveolar pressure

T — Surface tension

r — Radius of alveolus

This indicates that if surface tension is decreased, lung expansion can be accomplished more easily and even small alveoli can be maintained open for gas exchange at low distending pressures.

Two forms of LV currently exist:

- TLV (Total liquid ventilation)
- PLV (Partial liquid ventilation) or PAGE (Perfluro-carbon associated gas exchange)

In TLV, a volume of perflurocarbon equal to lungs FRC is instilled via an Endotracheal tube and tidal volume (VT) aliquots of liquid are subsequently cycled to effect gas exchange, often utilizing highly specialized apparatus. In PAGE, a volume of perflurocarbon equal to lungs FRC is instilled via ETT but the subsequent tidal ventilation is performed with respiratory gas administered via a standard mechanical ventilator at conventional sittings.

Greenspan et al were the first to report the clinical application of a liquid breathing technique.[10] They treated three premature infants with HMD who failed to respond to conventional ventilation, using TLV by a gravity flow devise. Therapy was limited to 2 cycles each of 5 minutes followed by regular gas ventilation. All patients showed marked improvement in compliance and oxygenation without any signs of homodynamic instability. This can be further improved with PLV as the high resistive component that contributes to increased airway pressure with TLV is largely obliviated.

However, Dose-response curves for various applications of LV need to be determined and new perflurocarbons developed the physical

properties of which will facilitate particular therapies. This type of ventilation is still experimental in nature and further study is indicated to asses long-term perflurocarbon toxicity particularly for application in preterm infants.

Supportive Therapy with Mechanical Ventilation

Sedation—Sedation is generally required to limit the distress and agitation associated with intubation and ventilation. Morphine infusion (0.1-0.2 mg / kg / hr) is generally used for this purpose. Other drugs like midazolam are sometimes added.

Muscle relaxation—Infants who continue to fight ventilation, particularly bigger / term babies and babies with PPHN are paralyzed using boluses of pancuronium to have effective ventilation. Prolonged muscle relaxation leads to fluid retention and reduction in compliance.

Blood gas monitoring-All neonates on ventilation require continuous monitoring of oxygen saturation and acid-base status.

Complications and Sequelae

A. Mechanical
   - ET obstruction-atelectasis
   - Equipment malfunction

B. Barotrauma and oxygen toxicity (BPD)
C. Air leak syndrome
D. Complication of invasive monitoring:
   - Peripheral arterial occlusion–infarction
   - Aortic thrombosis
   - Embolization

E. Anatomic
   - Subglottic stenosis
   - Palatal grooves
   - Vocal cord damage

Assessing the Outcome

It is important for a unit that offers ventilation to newborns to assess the outcome from time to time. Over the years, respiratory failure as a cause of mortality has come lower in order following intraventricular hemorrhage and sepsis. Regular statistical reviews should be performed to see the outcome of very low birth weight babies. In Indian setup, we can offer ventilation and surfactant therapy to babies more than 26 weeks gestation and more than 600 gm birth weight, but in smaller babies outcome may not be very good. It is therefore recommended that every NICU should weight the benefit of neonatal ventilation as per their outcome and make judicious use of technology.

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17 Chapter

High Frequency Ventilation

Jeffrey C Benson, Ramesh Sachdeva, Praveen Khilnani

Respiratory failure is a final common pathway for many hospitalized patients regardless of etiology. Conventional mechanical ventilation is the mainstay of support for these patients. Support strategies initially utilize minimal ventilator settings to achieve oxygenation and ventilation. As lung pathology evolves, increasing ventilator support may result in additional lung injury referred to as ventilator associated lung injury. When the disease process of the lung progresses and conventional positive pressure ventilator support are being increased, alternative modes of ventilation should be considered to maintain oxygenation and ventilation while preventing further lung injury.

VENTILATOR INDUCED LUNG INJURY

Insults to the lung tissue often result in a heterogeneous pattern of injury represented by areas of inflamed lung and areas of normal lung.[1] When providing positive pressure support to the diseased lung to overcome atelectasis and recruit alveoli, shear stress occurs opening the alveoli of the diseased lung and creating injury to the already compromised area.[2] Simultaneously, areas of normal lung are subjected to positive pressure required for the diseased areas of lung, thereby subjecting the healthy lung to injury. Lung injury from high pressure is referred to as barotrauma and when it is the result of volume it is referred to as volutrauma. Furthermore, prolonged exposure to $FiO_2 > 0.6$ has been implicated in furthering the inflammatory insult in the lung through oxidative damage via free radicals and absorbtive atelectasis.[2-5] Therefore, the use of positive pressure conventional mechanical ventilation may result in an iatrogenic insult to the already compromised lung referred to as ventilator associated lung injury. The stress on the lung tissue results in release of cytokines and inflammatory mediators, contributing to both local and systemic effects.[6] The local effects increase lung inflammation, worsen capillary leak, and decrease lung compliance. Ultimately, this lung injury will gradually result in escalating ventilator support and this further increases stress to the already compromised lung leading to ARDS. The systemic effects result in diffuse inflammation potentially causing or contributing to multi-organ system failure (MOSF).[7] Therefore, ventilator strategies should be utilized to provide optimal ventilation and perfusion, to minimize positive-pressure

related parenchymal damage, and enable highest possible recovery of compromised lung.[8]

PROTECTIVE STRATEGIES OF CONVENTIONAL MECHANICAL VENTILATION

In order to avoid ventilator associated lung injury, several protective strategies are commonly employed in clinical practice. Avoiding prolonged exposure to oxygen FiO_2 greater than 0.60 to minimize oxygen induced injury to the lung. Whether in volume or pressure support mode one should follow the peak and mean airway pressures to minimize volutrauma and barotrauma. Typically, the peak airway pressures less than 35-40 cm H_2O and peep between 5-15 cm H_2O are both consistent with currently accepted clinical practice.[5,7,9] When support reaches these points ($FiO_2 \geq 0.60$, PIP ≥ 35, Paw < 25 and PEEP ≤ 15), alternative strategies may be employed to support the respiratory system.

BASIC CONCEPTS OF HFV (HIGH FREQUENCY VENTILATION)

The basic concept of high frequency ventilation is to use smaller than physiologic tidal volumes (tidal volume $\leq$ dead space) at supraphysiologic rates to support ventilation and oxygenation. The underlying benefit is based on the premise that HFV will result in less barotrauma and volutrauma when compared to prolonged conventional ventilation support at high levels of support. The basic types of HFV are broadly classified and described in the following section.[2,10-13] The actual mechanisms of gas exchange in HFV rely on several mechanisms: principles of direct bulk convection, longitudinal (Taylor) dispersion, Pendeluft, asymmetric velocity profiles, cardiogenic mixing and molecular diffusion.[12]

TYPES OF HIGH FREQUENCY VENTILATION

High Frequency Positive Pressure Ventilation (HFPPV)

Typically capable on most conventional mechanical ventilators with a neonatal setting and low compliance tubing. Oxygen is supplied from a high-pressure gas source. Gas delivery and flow is provided by a pneumatic valve system delivering the oxygenated gas during inspiration. Thereby, inspiration is active and expiration is passive. Typical settings might include; tidal volumes (3-4 ml/kg) or $\leq$ dead space, rates range between 60 and 150, and inspiratory times are relatively short with I/E ratios of 0.3. Adjustments to normalize blood gases are similar to managing CMV.

High Frequency Jet Ventilation (HFJV) (Fig. 17.1)

Ventilation is delivered by low compliance, low volume tubing and a jet catheter inserted or built into the endotracheal tube which is attached to a special ventilator. The jet catheter is ideally positioned at the end of the

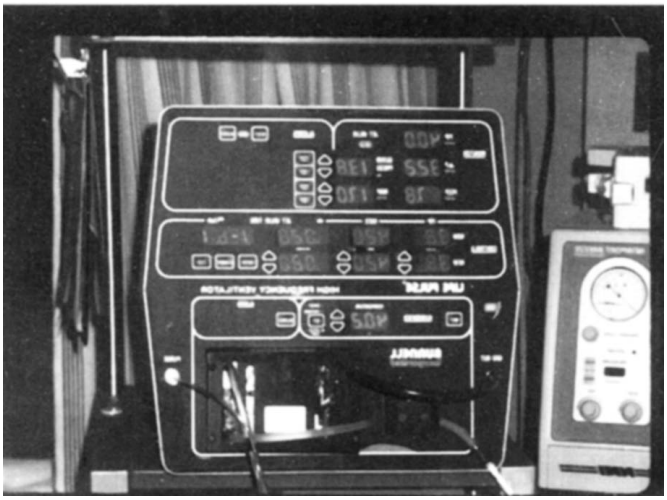


Fig. 17.1: Bunnell jet ventilator

endotracheal tube. This catheter creates the driving pressure for ventilation from high-pressure gas source. This gas source creates an airway driving pressure between 0-50 pounds per square inch and is adjusted by a valve. An additional valve creates high frequency sequential interruptions in the driving pressure. This creates small, rapid bursts of positive pressure coming from the jet catheter. The small interruptions are relative drops in airway pressure and allow for passive expiration. Thereby, the driving pressure in the airway is created by rapid burst of airway pressure resulting in active inspiration and expiration is passive. Typical settings often include: tidal volumes are either less than or equal to physiologic dead space (2-5 ml/kg), inspiratory times 10 to 50 percent of the inspiratory cycle, ventilator rates range between 300-1200. Attachments to the endotracheal tube may be used to maintain PEEP (valve) or provide oxygen reservoir (reservoir bag) in the spontaneously breathing patient.

High Frequency Oscillatory Ventilation (HFOV) (Fig. 17.2)

This type of ventilation features active inspiration as well as active expiration delivered by a special ventilator. Low volume, low compliance tubing is used to deliver support from a special ventilator. Flow is generated from a piston driven acoustic speaker cone, or diaphragm. Movement of this diaphragm creates sinusoidal oscillations in the airway pressure relative to the mean airway pressure. The fluctuations in airway pressure higher than the mean airway pressure create an inspiratory force, and pressure less than the mean, create a relatively negative or expiratory force. The tidal volumes < dead space are used, typically 1-3 ml/kg. Rates in frequency set between 1 to 60 Hz (60-3600 cycles per minute). In practice, mean airway pressure recruits lung volume, prevents atelectasis and thereby supports oxygenation along with FiO_2. The two main factors determining ventilation are Hz and delta P. Delta P is the pressure fluctuation relative to the mean airway pressure creating sinusoidal

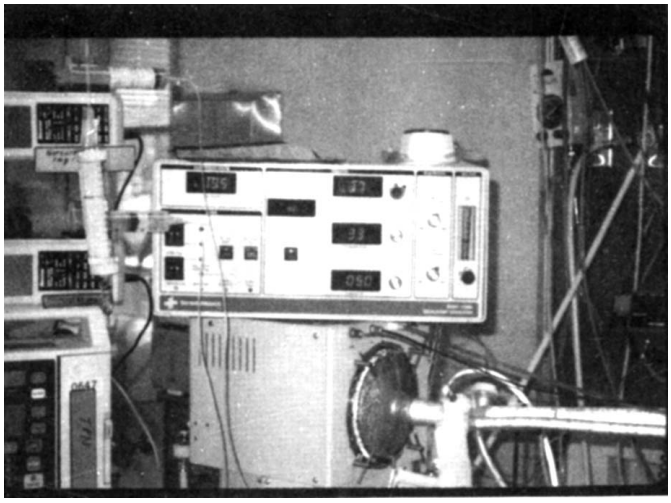


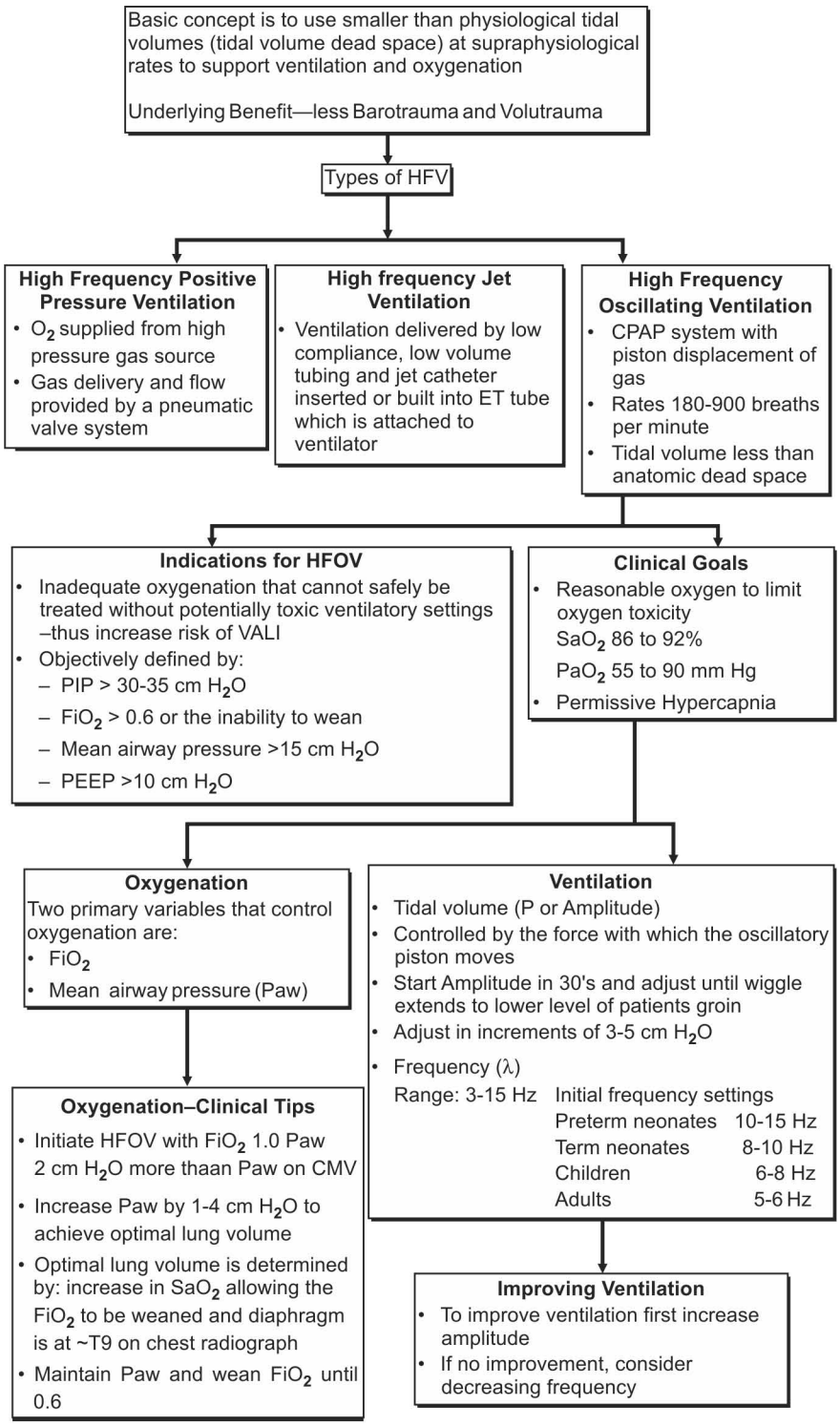
Fig. 17.2: Sensormedics oscillator

pressure fluctuations relative to the mean airway pressure. Hz determines the number of oscillations of delta P per unit time. At lower Hz, the ventilator is able to achieve most of the delta P, thereby generating effective ventilation and lowering the PCO_2. As the Hz increases, the oscillator is unable to achieve the full delta P. Sinusoidal wave of airway pressure is essentially dampened, reducing the size of the breath, resulting in less effective ventilation. Therefore, keeping the delta P constant and decreasing the Hertz will increase ventilation, and increasing the Hertz will decrease ventilation due to dampening, making each delta P less effective.

CLINICAL APPLICATION (FLOW CHART 17.1)

High-frequency ventilation represents an alternative means of ventilatory support in children when conventional ventilation does not work. In a prospective, randomized, crossover study involving 58 children with diffuse lung disease, two groups initially received either high-frequency ventilation or conventional ventilation.[14] Children receiving HFV alone had a better survival (94% vs. 60%), fewer days of supplemental oxygen, and a lower incidence of chronic lung disease (11% vs 30%), when compared with the control group receiving conventional ventilation. Fifty-eight percent of the patients who did not respond to conventional ventilation and crossed over to HFV survived, whereas 18 percent crossing over to conventional mechanical ventilation because of persistent respiratory failure survived. Futhermore, improvement in patient outcomes will occur as methods to control the mechanisms of lung injury are studied. Clinical trials involving adults with ARDS using corticosteriods, ibuprofen, prostaglandin E1, monoclonal antibodies against endotoxin, antioxidants, TNF monoclonal antibodies, interleukin receptor antagonist, surfactant and inhaled nitric oxide, will also provide additional adjunctive therapies to improve lung function and minimize the risks of ventilator support.[7]

Flow chart 17.1: High frequency ventilation



SUMMARY

High frequency ventilation provides an alternative form of positive pressure support to the critically ill patient with respiratory failure. Current theories in regard to ventilator associated lung injury and strategies of protective ventilation suggest that timely initiation of HFV might have a role as a protective strategy. Currently, there is a large effort working towards determining clinical outcomes for HFV and to provide appropriate evidence based rationale to the application of patient management.

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PRACTICAL ASPECTS OF HIGH FREQUENCY VENTILATION OF PEDIATRIC AND NEONATAL PATIENTS

High frequency oscillatory ventilation(HFOV) differs from conventional ventilation in that it provides rates of 120 to 1200 with volumes of 0.1 to 1.5 cc/kg. In comparison, conventional ventilation provides rates of 1 to 120 and volumes of 4 to 20 cc/kg.

Broadly speaking, indications for using HFOV include: Airleak, to reduce barotrauma, and finally when conventional ventilation is failing.

WHERE IS THE EVIDENCE?

Supporting data for high frequency oscillatory ventilation (HFOV) in acute lung injury are provided by animal studies.[1-7] These studies have demonstrated that HFOV diminishes the amount of ventilator-associated lung injury and improves gas exchange by attenuating alveolar edema and hyaline membrane formation. Comparison of lung-protective strategies of conventional ventilation (CV) and HFOV, in a rabbit model of ARDS, showed that HFOV seems to be associated with less pulmonary inflammation and may protect against biotrauma and ventilator-associated lung injury[7]

Several prospective randomized trials have compared HFOV, as the initial mode of ventilator therapy, with CV in preterm infants who have respiratory distress syndrome.[8–11] Results of these trials have been contradictory and there is no clear evidence that HFOV, compared with CV, offers important advantages.[11] Most studies evaluating HFOV in term neonates have included neonates with unresponsive respiratory failure who are candidates for ECMO (Extra corporeal membrane oxygenation).[12–15] These studies showed that 46-83 percent of these patients responded to HFOV and avoided ECMO. HFOV is now frequently used as rescue treatment for hypoxemic pediatric patients. Some studies of HFOV in patients failing CV strategies have demonstrated improved oxygenation and gas exchange in pediatric respiratory failure.[16-25] Only one prospective, randomized trial of HFOV in pediatric patients who had respiratory failure has been performed.[17] This trial showed that HFOV, using an optimal lung volume strategy, results in significant improvement in oxygenation compared with a conventional ventilatory strategy designed to limit increases in peak airway pressures. Furthermore, HFOV was associated with a lower frequency of barotraumas and improved outcome. In a cohort of pediatric patients submitted to HFOV after failure of CV, HFOV caused significant improvements of oxygenation variables, but patients with pre-existing lung disease had a higher rate of ECMO or death than patients with no pre-existing lung disease (64% vs 38%).[22] In a more recent retrospective study, survival in 19 pediatric ARDS patients treated with HFOV was significantly better than predicted by the Pediatric Respiratory Failure score but could not be predicted using several outcome scores or the oxygenation index in the first 24 hours.[23]

In another study,[26] good outcome in 21 pediatric patients with ARDS who received HFOV was associated with lower MAP (before HFOV and at 36 hours), lower P $(A\text{-}a)O_2$ at 6 hours, lower OI (oxygenation index) at 24 hours, and higher PaO_2/FiO_2 at 24 hrs of HFOV. In adult studies, patients failing CV who were then switched to HFOV showed improved oxygenation and ventilation, and HFOV was well-tolerated.[27–30] Moreover, the first prospective randomized trial in adults showed a trend towards a decrease in mortality.[29] Despite these encouraging reports, there is not enough evidence to conclude whether HFOV reduces mortality or long-term morbidity in children and adults with acute lung injury or ARDS.[31,32]

In the randomized study by Arnold et al,[17] survival rate was 66 percent in 29 HFOV-treated patients who had a Pediatric Risk of Mortality score of 11.5 and an OI, at enrollment, of 25.5. Eight of these patients (27.5%) were withdrawn from HFOV because of hypoxemia, hypercarbia, or severe air leak. Fedora et al[21] reported a mortality rate of 57 percent among 26 patients with ARDS who had an OI, before HFOV, of 9.6.[29]

In a more recent study,[25] survival rate was 56 percent among 32 pediatric patients with diffuse alveolar disease, failing CV. In the studies by Arnold et al and Fedora et al[17,21] mean length of CV was 50 and 143 hours, and in the study by Slee-Wijffels et al[25] median length of CV was 29.5 and 63 hours in the survivors and nonsurvivors, respectively.

In animal studies, there is evidence that HFOV may be more effective when used early in the course of respiratory failure.[31,33] A study by Rosenberg et al[16] suggested that time spent receiving CV before institution of HFOV may be an important factor related to survival and that prolonged CV may be a poor prognostic sign for a favorable response to rescue therapies. Fedora et al[21] also reported that the duration of CV before HFOV has a substantial influence on HFOV efficacy and patient survival in children with ARDS. In adult studies,[27,28] the duration of time spent on CV before the start of HFOV was also predictive of mortality. Early intervention with HFOV may be beneficial, perhaps due to the prevention of further ventilator-associated lung injury. In some studies, patients with primary respiratory failure demonstrated a significantly greater risk of improvement on HFOV and had a significantly lower mortality rate (12%) than patients with two and three or more organ failure (67% and 95%, respectively).[19] Sepsis and immunocompromised state were associated with increased risk of death in the study by Arnold et al.[22]

In a recent study on HFOV strategies published in Pediatr Crit Care Med 2006[34] ventilation strategy designed to allow use of HFOV as a relatively early intervention with a goal to reduce ventilator-induced lung injury, showed encouraging results.

Initiation of High Frequency Oscillation

It is important to initiate high frequency ventilation early if conventional methods of ventilation are failing. Impending respiratory failure is indicated by rising carbon dioxide levels and dropping oxygen levels despite ventilator adjustments to compensate.

Respiratory failure is defined as a $PaCO_2$ above 55 and a PaO_2 below 50.

The lung parenchyma in children is especially delicate and the high peak pressures utilized in conventional methods of ventilation can be harmful to the delicate lung tissue.

High frequency ventilation offers the advantage of improved CO_2 removal at lower peak pressures. Barotrauma occurs when the lung tissue is damaged due to the excessive pressures that can be created by conventional ventilation. However, high frequency ventilation can cause hemodynamic changes. This is due to the continuous pressures that are generated by high frequency ventilation, which cause increased pressures in the thoracic cavity.

WHY IS THIS IMPORTANT?

Increased thoracic pressures impede cardiac output. This, in turn, affects the blood pressure, and a vicious spiral can be created. In order to avoid this, it is important to carefully monitor the patient's hemodynamic status. Continuous pressure monitoring is crucial. Arterial lines are necessary when a pediatric patient is placed on high frequency ventilation. In addition to the continuous blood pressure monitoring, the arterial line also functions as the site of numerous blood draws for arterial blood gases. The ideal end results when using high frequency ventilation have no adverse damage to the lungs due to ventilation, and no neurological deficit. Prolonged periods of inadequate oxygenation can cause permanent brain damage.

It is important to know when to implement HFOV.

When Preparing to Change from Conventional to High Frequency Ventilation, What Preparations must be Made?

It is advantageous to have arterial line catheterization established. If the patient is a neonate, this may be an umbilical artery catheter. In pediatric patients, this can be any catheter placed in an artery. In addition, continuous monitoring of vital signs is important. The following points should be taken care of:

Monitoring

Blood pressure monitoring is especially important because high frequency ventilation can cause hemodynamic changes such as hypotension and / or decreased cardiac output. If the use of high pressure leads to a decrease in cardiac output, tissue and organ perfusion are affected. By carefully monitoring the urine output; kidney function, and thus organ perfusion, can be monitored.

As thoracic pressures change with the administration of high frequency ventilation, negative effects may result. It is especially important to obtain a chest X-ray (CXR) 30 to 60 minutes after the initiation of high frequency ventilation. This helps to determine whether or not the mean airway pressures are compressing the heart.

Expansion of the chest must also be monitored. The expansion of 8.5 to 9 ribs indicates proper inflation. Adjustments should be made to correct the expansion, as needed. As the lungs heal, they become more inflated; hyperinflation may lead to pneumothorax. Regular chest films must be taken to determine improvement or decompensation. Initially, chest X-rays should be taken every six hours. The care of patients receiving high frequency ventilation is very individualized. Policies regarding CXR intervals are set by each facility. Nitric Oxide is frequently used in conjunction with HFOV. It is a potent pulmonary vasodilator and works specifically on the pulmonary bed to help improve oxygenation. With increasing use of sidenafil in neonates for PPHN, use of nitric oxide has reduced mostly due to cost related issues.

Settings

Amplitude

High Frequency Ventilation is much more dependent on amplitude than on rate. How are the initial settings for high frequency ventilation determined? The first setting to consider is the amplitude, or delta P. The amplitude is similar to the tidal volume in conventional ventilation. The proper setting is determined by observing the patient to see how much chest excursion / movement occurs with oscillation. This **s**etting should be enough to vibrate or "wiggle" the thorax from the nipple line to the umbilicus. Settings are changed by 1-2 cm H_2O until the desired amplitude is reached. There is no exact calculation for setting the amplitude. Changes in the amplitude require readjustment of the mean airway pressure.

Frequency

The frequency, which is similar to the rate, is measured in hertz. There are rules by which to choose the setting for the hertz. Multiply the number of hertz times 60 and the exact rate is calculated. Below is a table for determining initial hertz settings (Table 17.1).

This table is taken from the recommendations by Sensormedics for use with the 3100A high frequency oscillating ventilator. Settings depend on the size of the patient and the disease process.

TABLE 17.1: Determination of initial hertz settings

1000 grams	15 Hz
1000-2000 grams	12 Hz
2.0-10 kg	10 Hz
13-20 kg	8 Hz
21-30 kg	7 Hz
> 30 kg	6 Hz
For Meconium Aspiration Syndrome	3-6 Hz

When initiating high frequency ventilation in the pediatric patient, begin with a hertz such as 6 or 7. This will allow for the greater lung capacity and lung volumes of older patients. Once again, the amplitude should be in accordance with the amount of "wiggle" seen on the chest. When ventilating the pediatric patient, adequate cardiac output must be maintained. The blood pressure must be within acceptable parameters. Without adequate circulation, there cannot be adequate tissue oxygenation.

What Steps are to be Taken if the Blood Pressure is not Adequate?

The first step is a fluid bolus of normal saline. Consider increasing the rate of intravenous maintenance fluids. This should improve blood pressure and cardiac output. If this is not sufficient, vasoactive infusions such as dopamine should be considered. These can be instituted in addition to the increase in intravenous fluids.

Input and output must be continually monitored in order to prevent fluid overload.

Mean Airway Pressure

The mean airway pressure (MAP) is to HFOV as peak airway pressure is to conventional ventilation. For a severe diffuse alveolar disease, the initial mean airway pressure should be set approximately 2 cm H_2O over what the value for peak pressure was on the conventional ventilator due to high initial opening pressure of alveoli. If compression of the heart is noted on CXR, a decrease in the mean airway pressure is necessary. The recommended decrease is 0.5 to 1 cm H_2O on the MAP (mean airway pressure) dial. A spontaneous pneumothorax is a complication that can result from high frequency ventilation due to a high mean airway pressure. Optimal pressures are desired at all times with high frequency ventilation. Optimal pressures can be defined as the amount of pressure necessary to ventilate adequately and maintain a normal $PaCO_2$.

FiO_2

An initial FiO_2 is selected to optimize pulmonary vascular resistance while the ventilator is opening the lungs. Use caution when administering high concentrations of oxygen to the neonate. Paralytic agents(muscle relaxants) may cause fluid retention, and this should be taken into consideration. The patient may be paralyzed initially, but paralytics should not be used for an extended period of time. As soon as tolerated by the patient, the agent should be discontinued.

Case Presentations

The following are case presentations of patients with whom high frequency ventilation was used. There is a discussion of how each case progressed and the reasoning behind each decision that was made. Each patient is different and may respond differently to the clinical decisions made. It is

important to assess and reassess the patient after each change. Vital signs are normal unless otherwise stated.

Case 1

A 27 week gestational premature infant with an admission weight of 1095 gm is admitted to rule out sepsis. The infant had been delivered to a G2P1 32-year-old mother who had received adequate prenatal care. He is admitted for pneumonia, fever 103°F, and a left upper lobe infiltrate. Upon delivery, the infant's pH is 6.90 and he is intubated with a 2.5 fr endotracheal (ET) tube. Positive pressure ventilation is administered with 100 percent O_2, and he is given intravenous fluids. A repeat umbilical blood gas pH is 7.10. Five meq $NaHCO_3$ are given intravenously and blood cultures are drawn. Intravenous Ampicillin and Gentamicin are given.

Another umbilical blood gas is drawn with results of pH (7.38) / CO_2 (37) / PO_2 (111) / HCO_3 (17) / -8.7. An initial dose of Surfactant is given (4.3 cc). This artificial surfactant is useful in immature lungs to help the alveoli stay open, which improves oxygenation.

Upon arrival to the NICU, oxygen saturations are sustained in the 80's by bagging with 100 percent oxygen. The infant is then placed on the high frequency oscillating ventilator with 100 percent O_2. Oxygen saturations fall into the 60's and the infant is then re-intubated with a 3.0 endotracheal tube. Nitric Oxide is started at 20 ppm (parts per million) for probable persistent pulmonary hypertension secondary to sepsis / pneumonia. Dopamine is started at 5 mcg / kg / min to improve renal function and organ perfusion. APGAR scores are 2 (1 min), 4 (5 min), and 6 (10 min). These are significant because the normal APGAR is 9 or 10.

What would be Appropriate Initial Oscillator Settings? Why?

Initial oscillator settings are: FiO_2—100 percent, Mean airway pressure MAP—17, Amp—26, Hz—15. The correct guidelines for selection of the initial amplitude settings are to deliver enough amplitude to see a"wiggle" from the nipple line to the umbilicus. The FiO_2 should initially be set at 100 percent.

The ABG results on these settings are 7.38/41/45/24/-0.6.

What is the main problem with this blood gas and what intervention(s) need to be taken?

This blood gas shows adequate acid / base balance, but severe hypoxia: the main problem is oxygenation. An increase in the MAP can be instituted to increase oxygenation. This will open the airways more, similar to the way positive end-expiratory pressure (PEEP) does in conventional ventilation. The guideline for increasing the mean airway pressures is to increase in increments from 0.5 to 1.0 cm H_2O. The MAP was increased to 18.

Nitric oxide is also started at this time. Nitric oxide is a pulmonary vasodilator and is indicated for the treatment of neonates with hypoxic respiratory failure. It dilates the blood vessels of the lungs, so they can carry more oxygen and is used in conjunction with ventilatory support and other appropriate agents.

The follow-up blood gas is 7.28/65/76/30/+1.6.

Interpret this gas and determine the appropriate intervention.

This result reflects an uncompensated respiratory acidosis.

In order to decrease the CO_2, the amplitude is increased to 30.

A repeat blood gas is drawn after the change in HFOV settings. The results are 7.35/51/172/28/+1.7

Is this an acceptable blood gas? Do any interventions need to be made and, if so, what are they?

The amplitude is increased to 32 in order to decrease the CO_2 to within normal limits (35–45). The oxygenation status is excellent, therefore the FiO_2 is decreased to 90 percent. This is a premature neonate; prolonged exposure to high amounts of oxygen has the potential to cause many problems, such as blindness. The ABG results after the changes are made are 7.38 / 42 / 74 / 24 / 0.2.

Later ABG results are 7.59/27/144/25/+6.0.

Interpret this gas and explain the interventions.

This gas reflects a respiratory alkalosis with hyperoxygenation.

The amplitude is decreased to 22 to allow the CO_2 to rise, and the FiO_2 is further decreased to 80 percent. Suddenly, the oxygen saturation drops to the 70's. The infant is suctioned for a moderate amount of blood. When placed back on HFOV the saturation then falls into the 40's and the heart rate drops to the 80's. A large amount of frank blood is suctioned from the ET tube. Epinephrine is instilled into the endotracheal tube to assist in hemostasis.

A portable chest X-ray is taken.

What is causing the above condition?

Due to the sudden onset of hemodynamic changes, a pneumothorax is suspected and the portable chest X-ray shows a large left pneumothorax.

A 10 Fr chest tube is place in the fourth intercostal space, mid-axillary, with an audible resolution of the pneumothorax. Epinephrine is a vasoconstrictor and is used in this situation to slop bleeding in the lungs. Any time the intrathoracic pressure increases, there is an increased risk for pneumothorax. As the mean airway pressures are increased, the risk for potential negative side effects are increased; the lung tissue in premature neonates is very delicate.

The ABG results after chest tube placement are 7.31 / 35 / 129 / 18 / -8.0. Interpret this gas and give the intervention. This is a partially compensated metabolic acidosis with hyperoxygenation. This acidosis has already been partially compensated for by blowing off CO_2 and now must be treated pharmacologically.

Sodium bicarbonate is given intravenously. As the pneumothorax resolves, the infant is weaned off high frequency ventilation. As the neonate grows, so does the lung tissue. The infant is able to be changed to conventional ventilation and later extubated. He is then placed on oxygen via nasal cannula at an FiO_2 to maintain the oxygen saturation greater than 92 percent. The infant is discharged thirty days after extubation.

Case 2

A 14-year-old female is admitted with a decreased level of consciousness and abdominal bleeding. She also complains of abdominal pain, diaphoresis, and cramping in the left upper quadrant and periumbilical area. A diagnostic laparoscopy is performed, noting copious bleeding from a hemorrhagic cyst. She experiences hypotension and a decreased hemoglobin and hematocrit. Packed red blood cells are transfused. After fluid and blood resuscitation, an exploratory laparotomy is performed. A 2000cc hemoperitoneum with a small amount of bleeding from the right ovary is discovered.

The initial ABG on room air is 7.32/52/68/26.

What is happening? From the given data, is her condition prone to deteriorate? What are appropriate initial ventilator settings?

This blood gas indicates a potential for respiratory failure. The CO_2 level is higher than normal without any form of compensation. Due to this lack of compensation, we determine that this is an acute event.This patient is intubated to protect her airway. Because of the potential for respiratory failure, it is preferable to intubate as an elective procedure, rather than as an emergency measure during an arrest situation. This patient has a great risk for hemorrhagic shock because of the amount of blood loss from the cyst. Close monitoring of the hematocrit and hemoglobin is important. In addition, it may be necessary to place an arterial catheter for continuous blood pressure monitoring and laboratory draws.

Despite all efforts using conventional ventilation via pressure regulated volume control (PRVC), a marked decrease in the PaO_2 ensued. PRVC is a mode of ventilation with the Servo 300 that allows volume ventilation with minimal pressures. This minimizes barotrauma, but ventilates very effectively in difficult situations to ventilate patients. The ABG results are 7.47 / 31 / 54 / 22 / +1.0 on settings of: rate- 20, tidal volume- 350, and FiO_2- 100 percent.

Is this a ventilation or oxygenation problem?

The pH is normal, the $PaCO_2$ is only slightly below normal, and the PaO_2 is 54; this is clearly an oxygenation problem.

High frequency oscillation ventilation is initiated due to the need to minimize the insult to the lungs and try to recruit more alveoli and improve oxygenation.

What would be appropriate initial settings for HFOV?

Initial ventilator settings are FiO_2—100 percent, Hz—6.5, amp—45, and MAP—35.

The amp setting is set just high enough to cause a wiggle from the nipple line to the umbilicus. The amp setting is set just high enough to cause a wiggle from the nipple line to the umbilicus.

The initial ABG results are: 7.32 / 48 / 203 / 25 / -1.5.

What should be done next?

Oxygenation has improved, but the $PaCO_2$ is increasing while the pH is decreasing. This is indicative of respiratory acidosis. The goal here is to decrease the CO_2. Hyperoxygenation is not necessary.

What is necessary to achieve this goal?

First, a decrease in the FiO_2 is necessary to bring the PaO_2 nearer to normal. Increasing the amplitude will help decrease the $PaCO_2$.

Her condition seems to be stabilizing.

The next ABG that is drawn shows the results: 7.04 / 113 / 376 / 30 / -4.8.

Does this ABG indicate acidosis or alkalosis; metabolic or respiratory? What interventions should be taken?

Should sodium bicarbonate be given? Why, or why not?

The last blood gas indicates a severe respiratory acidosis. Because the bicarbonate level is 30, there is little metabolic involvement. In fact, the bicarbonate levels have started to rise to help the pH increase. In other words, there is some compensation. This is having no effect on the pH, which is still grossly abnormal.

Sodium bicarbonate is not indicated for this blood gas because the cause is respiratory, not metabolic.

A chest X-ray is taken at this time and reveals rib expansion to the eighth rib. The mean airway pressures will expand the lungs to various rib expansions. The patient is suctioned for a large amount of thick secretions. The MAP is increased and the repeat ABG results are: 7.13 / 93 / 225 / 31 / +1.5.

What does this indicate? What are the options for the ventilator?

Because the rib expansion should include 8.5 – 9 ribs, the MAP is increased to help improve oxygenation. In addition, the Hz may also be decreased to lower the CO_2. The Hz is decreased to 5 and the amp is increased to 50. This will allow a faster rate and larger tidal volume.

The repeat ABG is 7.16 / 66 / 314 / 23 / -7.0.

The MAP is then decreased to 27.7 and the Hz is decreased to 4. The repeat ABG is 7.34 / 50 / 128 / 27 / +1.0

Do you agree with these changes? Why?

The MAP was decreased due to evidence of hyperoxygenation. To lower the CO_2 even more, the Hz was decreased. As this case progresses over the next five days, the FiO_2 and the MAP are weaned gradually.

When would be an appropriate time to switch to conventional ventilation? Why?

The goal is to wean the mean airway pressure lower. When the mean airway pressure is about 5 cm H_2O over what it was on conventional ventilation, it is time to change ventilation modes. The amplitude setting is another indicator that it is time to switch to conventional ventilation. As the patient recovers, the amplitude is weaned. This indicates that the lungs are healing and recovering. It is then time to change the mode of ventilation to a conventional mode. When the amplitude is weaned to a low number, such as 18 or 20, it also indicates it is time to change to conventional ventilation. When placing the patient back on conventional ventilation, the settings might be temporarily higher to allow the patient to compensate for the change in ventilator modes.

Take Home TIPS

Ventilation to high frequency, remember these tips:

1. Set the MAP at 2-4 cm H_2O over the value used on conventional ventilation.
2. Set the amplitude to see a "wiggle" from the nipple line to umbilicus.
3. Set the hertz according to table listed.
4. Set the FiO_2 at 100 percent.
5. Obtain a chest X-ray approximately 30-60 minutes after the initiation of high frequency ventilation.
6. The rib expansion on X-ray should involve 8.5 – 9 ribs.
7. Obtain frequent arterial blood gases to monitor progress.
8. Break the circuit only when absolutely necessary. Suction the endotracheal tube as necessary.
9. Wean the ventilator settings as tolerated.

Is there another way of practice of HFOV?

Different institutions have different protocols, but the essential principles and goals remain same: To provide gentler ventilation with least barotrauma and FiO_2 causing least hemodynamic compromise.

Following is a protocol from Stanford hospital and clinics respiratory care services:

STANFORD Hospital and Clinics Recommendations and Guidelines for Implementation of High Frequency Oscillatory Ventilation (HFOV)

Indications and Patient Selection

1. Patients with severe ARDS requiring an $FiO_2 > 0.60$ with a mean airway pressure (Pmaw) > 24 cm H_2O may be considered for a trial of HFOV if a "lung protective" target Pplat < 30 - 35 cm H_2O cannot be maintained with pressure control ventilation. In practice, patients considered for HFOV have generally been tried on "high" PEEP and/or pressure control ventilation (PCV) with extended inspiratory times to raise Pmaw. A Pmaw =24 cm H_2O while on conventional ventilation is a reasonable threshold to consider changing to HFOV. Early institution of HFOV in patients deteriorating on conventional mechanical ventilation may be important to improved survival, although this has not yet been rigorously established.
2. Failure to improve the oxygenation within the first 24–48 hours is indicative of a poor response to HFOV, which may be prognostic for a decreased likelihood for survival. For example, patients with late phase fibroproliferative ARDS, when the alveolar architecture is severely damaged, are less likely to respond.

Patient Preparation

1. Prior to starting a patient on HFOV, it is imperative that the patient's airway is suctioned and known to be patent. If fiberoptic bronchoscopy is indicated, it should be performed before initiating HFOV.

2. Ensure adequate titration of sedation, analgesia, and neuromuscular blockade while the patient is still on conventional ventilation. The patient's intravascular volume status should be reassessed given that a higher Pmaw will be used with HFOV, leading to the potential for hypotension secondary to elevated intrathoracic pressures and reduced preload IV.

Initial HFOV Settings

1. **Oxygenation:** The main determinant of oxygenation during HFOV is the Pmaw, which is generally initiated at 5 cm H_2O higher than the Pmaw noted during conventional ventilation. Hemodynamically unstable patients may be started on a Pmaw either the same or 2-3 cm H_2O above Pmaw during conventional ventilation. Brief hypotension shortly after starting HFOV is usually managed with a trial of fluid boluses to improve preload. FiO_2 is usually set at 1.00 after the transition to HFOV, and then tapered using oximetry guidance to maintain SpO_2 > 90 percent. If the SpO_2 (or PaO_2) has not improved enough to allow weaning of FiO_2, the Pmaw is raised in 2-3 cm H_2O increments at 30-60 minute intervals in the hope of improving lung recruitment. The time course of oxygenation change after initiation of HFOV (or after increasing Pmaw) is variable. Some patients may slowly improve oxygenation only after a period of several hours. Vigilance and patience are required during the early phase of treatment. The maximum Pmaw generally obtained with the SensorMedics 3100B is 45–55 cm H_2O. Patients with large bronchopleural fistulas or endotracheal cuff leaks may have difficulty achieving a desired Pmaw without increasing the bias flow. In some patients with very severe air leaks, a maximum bias flow (60 L / min) may be required.
2. **Ventilation:** The main determinants of $PaCO_2$ elimination are the pressure amplitude of oscillation (P) and the frequency setting (hertz). Increasing the amplitude and decreasing the frequency (Hz) will increase the delivered tidal volume and lower the $PaCO_2$. Conversely, decreasing amplitude and increasing frequency (Hz) will reduce delivered tidal volume and allow $PaCO_2$ to rise. The amplitude is generally initiated at either a value where the patient's chest vibrates down to their mid-thigh. Alternatively, initial amplitude may be set to observe adequate "chest wall vibration". Initial frequency is usually set at 5 Hz. Patients who demonstrate rapidly rising $PaCO_2$ on HFOV should have aggressive increases in amplitude (10 to 20 cm H_2O) and reduced Hz to the lowest value achievable (3 Hz on the SensorMedics 3100B). An adjunct to improving $PaCO_2$ elimination is to briefly disconnect the patient from HFOV and vigorously manually ventilate with a PEEP-valve equipped bag. Aggressive action is required for a rapidly rising $PaCO_2$ during initiation of HFOV because improvements in $PaCO_2$ do not occur as quickly as when changes are made to conventional ventilators. An ABG should be drawn 15 to 20 minutes after starting HFOV to determine the trend of the $PaCO_2$. Subsequent ABG's are generally obtained at 30 to 60 minute intervals until stabilization occurs.

Guidelines for Initial HFOV Settings

1. Prior to initiating HFOV, perform a recruitment maneuver on the oscillator by increasing Paw to 40 cm H_2O for 30-40 seconds. NOTE: the oscillator should be OFF during the maneuver. Immediately abort the maneuver if hemodynamic compromise occurs.
2. Set initial Paw at 5 cm H_2O above conventional ventilator Pmaw.
3. Set power to achieve initial amplitude at chest oscillation to mid-thigh.
4. Set Hz at 5. Set IT to 33 percent (may increase to 50% if difficulty with oxygenation; this may further raise carinal pressure an additional 2-4 cm H_2O).
5. If oxygenation worsens, increase Pmaw in 2-3 cm H_2O increments after 30 minutes until maximum setting (approximately 45-55 cm H_2O).
6. If $PaCO_2$ worsens (but pH > 7.2), increase amplitude in 10 cm H_2O increments after 30 minutes up to the maximum setting. After maximum amplitude is achieved, if necessary, decrease Hz to the minimum setting of 3 Hz.
7. If severe hypercapnea occurs, with pH < 7.2, bag patient, set maximum amplitude, Hz at 3, and try a small cuff leak (5 cm H_2O and then compensate bias flow); rule out endotracheal tube obstruction.
8. If oxygenation improves, gradually wean FiO_2 to 0.40, then slowly reduce Pmaw 2-3 cm H_2O after 4–6 hours until 22–24 cm H_2O range.
9. When the above goal is met, switch to PCV (initial settings: peak pressure titrated to achieve delivered VT 6 ml/kg IBW, Pplat < 30-35 cm H_2O), I:E 1:1, PEEP 12 cm H_2O, rate 20–25, Paw should be 20 cm H_2O (+/- 2 cm H_2O).

Weaning from HFOV

The principal goal of using HFOV in treating patients with ARDS is to achieve a nontoxic FiO_2 (< 0.60) while minimizing ventilator induced lung injury. When patients respond with improved oxygenation, the first weaning maneuver therefore is to reduce the FiO_2 before any reduction is considered in Pmaw. A reduction of FiO_2 to 0.40 with a target SpO_2 > 90 percent before attempting reductions in Pmaw is recommended. If the patient can maintain a SpO_2 > 90 percent on a FiO_2 of 0.40, a gradual reduction of Pmaw (e.g. decrease 1– 2 cm H_2O after 30 minutes as tolerated) should be attempted. If the SpO_2 decreases during Pmaw reduction, resume the previous Pmaw that was able to maintain a SpO_2 > 90 percent on FiO_2 of 0.40. Perform an ABG and CXR for every total Pmaw reduction of 5 cm H_2O. **Once a Pmaw of 20–24 cm H_2O has been achieved while maintaining a FiO_2 of 40 percent, the patient can be switched back to a trial of conventional ventilation.** Obtain an arterial blood gas 15-20 minutes after transfer to conventional ventilation to guide further ventilator adjustments.

Potential Complications

1. **Hypotension:** Occasionally, patients will develop hypotension shortly following transfer to HFOV or as Pmaw is raised. This usually implies relative hypovolemia and responds to intravenous fluid boluses and/or vasopressors as indicated.

2. **Pneumothorax:** Tension pneumothorax occurring during HFOV may not cause changes to the displayed Pmaw or amplitude as the patient develops progressive hypotension and desaturation. A high index of suspicion is necessary for pneumothorax and confirmation (if time permits) requires an immediate CXR. It may be difficult by auscultation alone to detect the side of the pneumothorax during HFOV secondary to background noise of the ventilator and the diffuse transmission of airway sounds. The visual loss of chest oscillation that usually occurs on the affected side may provide an important physical sign.
3. **Endotracheal tube obstruction**: Subtotal occlusion of the endotracheal tube may result in refractory hypercapnea. An abrupt rise in $PaCO_2$ and loss of visual chest oscillation in an otherwise stable patient may be secondary to an obstructed or narrowed endotracheal tube. A suction catheter should be passed immediately to ensure patency of the endotracheal tube.

CONCLUSION

Ventilation strategy should be designed to avoid exposure to prolonged aggressive conventional ventilation and to **use HFOV as a relatively early intervention**, with a goal to reduce ventilator-induced lung injury and occurrence of intractable respiratory failure. Clinical objectives in the management of acute lung injury and ARDS focus on the prevention of ventilator-associated lung injury through lung protective strategies, using small tidal volumes and high positive end-expiratory pressure levels. HFOV offers the potential to maintain adequate gas exchange without imposing the large pressure swings and tidal volumes associated with ventilatory-induced lung injury.

However, randomized controlled trials are needed to identify its benefits over conventional modes of mechanical ventilation and to establish the optimum timing of HFOV initiation.

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APPENDIX

High frequency ventilation: Management Strategies with High Frequency Ventilation in Neonates and children Using the SensorMedics 3100A High Frequency Oscillatory Ventilator.

Sensor Medics Oscillatory Ventilator 3100A

A true high frequency oscillator with a diaphragmatically-sealed piston driver. Theoretically capable of ventilating patients up to 30 kg. Tidal volume typically delivered approximately 1.5-3.0 cc/kg (< dead space). Extremely efficient ventilation secondary to active expiratory phase, but not capable of delivering sigh breaths.

INITIAL SETTINGS

A. **Frequency**: Set initially at 10 Hz (600 BPM) for term infants and 15 Hz (900 BPM) for premature infants (< 2.5 kg). For children between 6-10 kg, use 8 Hz, between 10-20 kg, use 6 Hz and between 20-30 kg, use 4 Hz for an initial setting.

B. **Inspiratory time (IT):** Set initially at 33 percent (e.g. 22 msec at 15 Hz, 41 msec at 8 Hz, 55 msec at 6 Hz).
   1. Warning: The percent of IT should never be increased because it will lead to air trapping and fulminant barotrauma. Total IT should only be increased by decreasing frequency, thus leaving the I:E ratio constant. IT can be decreased to 30 percent to heal airleaks.
   2. I:E ratio: 1:2 (3-15 Hz), at 33 percent IT

C. **Power:** A rough representation of the volume of gas generated by each high frequency wave. Range (1.0 - 10.0). Maximum true volume of gas generated by the piston is 365 cc. Maximum amplitude or volume delivered is highly variable and depends on the following factors: circuit tubing (compliance, length and diameter), humidifier (resistance and compliance - water level), ET tube diameter and length (FLOW is directly proportional to r^4/l, where r = radius of airway and l = length of airway), the patient's airways and compliance.
   1. Set the POWER initially 2.5 if wt < 2.0 kg, 3.0 if wt 2-2.5 kg, 4.0 if wt 2.5-4.0 kg, 5.0 if wt 4.0-5.0 kg, 6.0 if wt 5-10 kg, 7.0 if wt 10-20 kg. Chest wall needs to be vibrating. If not vibrating, increase power.
      Check ABG's every 15-20 min until $PaCO_2$ is 40-60, i.e. titrate POWER setting based on $PaCO_2$ desired. Many HFOV centers have you order amplitude or delta P to regulate ventilation instead of power. We have decided that the Power setting is a more reliable way of adjusting this ventilator and thus we order changes in power in order to regulate ventilation.
   2. Alveolar ventilation is directly proportional to POWER, therefore the level of $PaCO_2$ is inversely proportional to the power.
   3. During HFOV, alveolar ventilation (Ve) = $(TV)^2f$ as compared to CMV where Ve = TV(R). Thus, we primarily adjust the power (amplitude) to change tidal volume in order to manipulate ventilation.
   4. *Management of ABG's (Ventilation - Ve):*
      a. Change POWER by 0.2-0.3 to change CO_2 ± 2-4 mm Hg
      b. Change POWER by 0.4-0.7 to change CO_2 ± 5-9 mm Hg

c. Change POWER by 0.8-1.0 to change CO_2 ± 10-15 mm Hg
d. *Warning:* It is extremely important to normalize $PaCO_2$ rapidly by weaning Power in order to avoid volutrauma from excessive tidal volumes. Thus, check ABG's frequently (Q15-20 min) and decrease POWER accordingly until $PaCO_2 > 35$. $PaCO_2 < 35$ correlates with an increased risk of pneumothorax. Thus to minimize the risk of volutrauma, it is important to use the least amount of TV (POWER or AMPLITUDE) possible to achieve ventilation.
e. If $PaCO_2$ still remains elevated at high POWER setting (> 8.0), decrease FREQUENCY by 2 Hz every 15-20 minutes until maximum tidal volume is reached (3-4 Hz at a POWER of 10.0). The lower frequency leads to a longer IT which results in a larger tidal volume of gas displaced towards the infant. This increased TV leads to increased alveolar ventilation (on HFOV, $Ve = (TV)^2f$.

5. *Manual ventilation:* Hand bagging while on the SensorMedics Ventilator should be avoided secondary to the risk of barotrauma due to over distention. Suctioning should be performed using just the ventilator breaths alone (an inline suctioning adapter would be best). If bagging has to be done, the PIP while bagging should not exceed 8-10 cm above the MAP and a PEEP of 6-8 cm should be maintained as tolerated.

D. **MAP:** Oxygenation on HFOV is directly proportional to MAP which is similar to CMV, however with the SensorMedics HFOV all of the MAP is generated by PEEP. Thus, during HFOV: MAP=PEEP.
1. Initial Settings:
   a. Neonates—Initial MAP should be 2-4 cm above the MAP on CMV.
   b. Infants / Children—Initial MAP should be 4-8 cm above the MAP on CMV.
   c. If starting immediately on HFOV, use a MAP of 8-10 cm in neonates and 15-18 cm in infants / children.
2. Management of ABG's (Oxygenation a MAP):
   a. If not oxygenating adequately at initial MAP (12-18 cm) obtain CXR to assess lung volume. If lung is not hyperinflated (flattened diaphragm) or is below optimal lung volume 9-10 ribs then increase MAP by 2-4 cm every 20-30 minutes until adequate oxygenation is achieved or lung starts to become overinflated (e.g. FiO_2 0.6-0.7 increase by 2-4 cm, FiO_2 1.0 increase by 4-8 cm).
   b. Maximum potential MAP = 40-45 cm
   c. Warning: If oxygenating adequately, but the lung is hyperinflated, immediately decrease MAP by 1-2 cm every 2-4 hours until lung volumes return to normal. If the lung is allowed to remain hyperinflated for prolonged periods of time the risk of barotrauma increases dramatically.
   d. If not oxygenating with lung becoming hyperinflated, you can decrease frequency as a way to increase IT while keeping I:E ratio constant.

MANAGEMENT STRATEGIES FOR THE SENSORMEDICS 3100

The SensorMedics HFOV is usually used for premature infants, term infants or young children with respiratory failure not responsive to CMV. The Infant Star HFV with its ability to oxygenate using less MAP than the SensorMedics due to the use of an occasional sigh breath (1-4 per min) is also recommended for premature infants with respiratory failure.

A. **Term infant with severe respiratory failure (PPHN, MAS, GBS pneumonia, RDS):** Start at a frequency of 10 Hz and a Power of 3.0 to 5.0. Initial MAP 4 cm

above MAP while on CMV. Check CXR 2 hours after converting to HFOV, then adjust MAP to achieve optimal lung volume (9-10 ribs expanded). If not oxygenating, increase MAP by 2 cm every hour until oxygenation improves. Adjust Power to keep $PaCO_2$ to 45-55.

B. **Airleaks:** Pneumothorax or PIE—The goal is to minimize both tidal volumes and peak pressures generated by any given TV. Tolerate increased FiO_2 requirements (0.6-1.0) in order to keep MAP at a minimum. Practice permissive hypercarbia and accept high $PaCO_2$'s to minimize the TV. Use a FREQUENCY of 12-15 Hz in order to minimize both total IT and TV in order to heal the airleak. Also decrease IT to 30 percent.

C. **ARDS:** The goal is to minimize volutrauma, barotrauma and oxygen toxicity. Thus use the minimum POWER possible at the appropriate FREQUENCY in order to keep $PaCO_2$ adequate (e.g. 55-65 mm Hg). Increase MAP as high as necessary to keep $FiO_2 < 1.0$. Also decrease frequency to increase IT to improve oxygenation.

D. **RDS:** Give surfactant replacement therapy using manual bagging. Start with frequency of 15 Hz, IT of 33 percent. Use MAP of 8-10 cm or 2 cm above MAP on CMV. Wean FiO_2 until < 0.50 then MAP as tolerated to avoid overinflation. Wean power/amplitude to keep $PaCO_2$ 45-60 mm Hg. Follow blood gases after 30-60 minutes after surfactant until stable and wean appropriately to avoid hypocarbia.

E. **Rescue Therapy For Premature Infant With RDS:** To be used for premature neonates who can't ventilate on either CMV or the Infant Star HFV or who require a MAP > 20 cm to achieve oxygenation while on the Infant Star. Use initial frequency of 15 Hz, Power of 3.0-4.0, MAP 2 cm above MAP on the Infant Star HFV, or MAP 4 cm above the MAP on CMV.

F. **BPD:** The goal is to minimize volutrauma, barotrauma, atelectatrauma, biotrauma and oxygen toxicity. Use minimum power/amplitude to keep $PaCO_2$ adequate (e.g. 50-70 mm Hg). Increase MAP as necessary to keep $FiO_2 < 0.50$ if possible. Use IT of 33 percent. Use frequency of 10-15 Hz: Use the lower frequencies if having difficulty with oxygenation, use the higher frequencies if having problems with hypocarbia or PIE.

G. **Other potential indications:** CHF/Pulmonary Edema, Chest Physiotherapy, Hypoplastic Lungs and Post-op Heart Patients

H. **Not beneficial for asthma:** Increased risk of air trapping with reactive airway disease.

WEANING

A. **Oxygenation:** Once oxygenation is adequate and the patient is ready to be weaned, follow these steps:
   1. First only wean FiO_2 until < 0.60 unless hyperinflated.
   2. Once $FiO_2 < 0.60$ or hyperinflated, decrease MAP by 1 cm after 4-8 hours; if OXYGENATION is lost during weaning then increase MAP by 3-4 cm to restore lung volumes and begin weaning again, but proceed more slowly with decreases in MAP.
   3. Minimal MAP is 8-16 cm with $FiO_2 < 0.50$, at this point one can convert to CMV or remain on HFOV while the patient continues to heal (e.g. 8-12 cm < 2.5 kg, 13-16 cm > 2.5 kg).

B. **Ventilation:** Reduce POWER by 0.2-0.3 units per change whenever $PaCO_2$ decreases below threshold, until minimal POWER is reached (1.5-4.0) depending on the size of the patient. If frequency is below the standard frequency for the patient's weight, then first wean by increasing frequency

back to baseline which also decreases the tidal volume, then decrease power as described.

1. Extubation—Neonates are ready to be extubated for a trial of NPCPAP when they meet the following criteria:
   a. MAP < 10 cm, FiO_2 < 0.40 and power < 2.5 then use NPCPAP of 7-9 cm.
2. Conventional Ventilation—Term neonates are ready for conversion to conventional mechanical ventilation (IMV or SIMV) when they meet the following criteria:
   a. MAP < 16-17 cm, FiO_2 < 0.40-0.45 and power < 4.0
   b. To convert to conventional mechanical ventilation (CMV) use MAP 3-4 cm less than the MAP on HFV [e.g. MAP = 16-17 on HFV, use a MAP of 12-13 on CMV (PIP = 26, PEEP = 8, Rate = 40, IT = 0.4)].

COMPLICATIONS ASSOCIATED WITH HFOV

A. Hyperinflation or Barotrauma: increased MAP.
B. Secretions: a suctioning.
C. Hypotension: increase MAP, and rule out other causes (e.g. pneumothorax, sepsis, dehydration, etc.).

Courtesy: Jonathan M Klein, MD Iowa Neonatology Handbook

18 Chapter

Inhaled Nitric Oxide

Rita Singh, Praveen Khilnani

Since the discovery of endothelium derived relaxing factor and its subsequent identification as nitric oxide,[1] recognition of its potent vasodilator properties and its unique ability to be delivered as a gas to the lung, inhaled nitric oxide (INO) has become an exciting new treatment for several disorders, characterized by pulmonary hypertension and pulmonary vasoregulation.

Endogenous NO

NO is produced by L-argine by a family of enzymes called nitric oxide synthase (NOS) which exist in constitutive and inducible forms.[2] Constitutive NOS is always present, is calcium dependent and produce low levels of NO intermittently, which is a major endogenous regulator of vascular tone. In contrast the inducible NOS is activated by cytokines and endotoxins, once induced it produces large amounts of NO. The pathophysiological role of this nitric oxide is evident in a variety of disease including septic shock, asthma, and reperfusion endogenous injury, etc. (Fig. 18.1).

Clinical Pharmacology of INO

NO binds rapidly to iron in heme moiety of proteins such as guanylcyclase, hemoglobin and electron transport chain. Activation of guanylcyclase

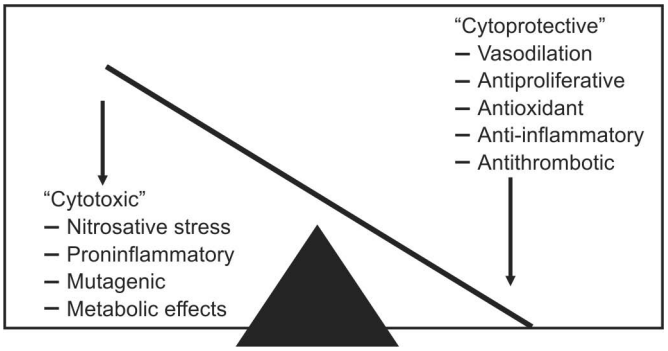

Fig. 18.1: Inhaled nitric oxide therapy: A balance between cytoprotective and cytotoxic effects

results in production of cyclic guanosine monophosphate (cGMP) which leads to vasodilation, and relaxation of smooth muscles of cardiovascular, respiratory, gastrointestinal and genitourinary system. Because it binds to heme, it gets inactivated in blood and does not enter systemic circulation. This accounts for selective effect of INO on pulmonary circulation.[3]

INO appears to increase the partial pressure of arterial oxygen (PaO_2) by dilating pulmonary vessels in better ventilated areas of the lung, redistributing pulmonary blood flow away from lung regions with low ventilation / perfusion (V / Q) ratios towards regions with normal ratios.

Persistent pulmonary hypertension of newborns (PPHN).

At birth, the pulmonary circulation changes dramatically. Pulmonary blood flow increases 8-10 fold and pulmonary arterial pressure decrease to less than half systemic levels in the first 24 hours of life.[4,5] Although release of vasoactive mediators, increased oxygenation, establishment of an airliquid interface have been shown to play a central role in transition of pulmonary circulation,[6] if postnatal adaption of pulmonary circulation does not occur, a clinical syndrome, PPHN results.

It is characterized by extrapulmonary right to left shunting across the foramen ovale and ductus arteriosus, pulmonary hypertension and severe central hypoxemia, that is not responsive to high concentrations of inspired oxygen. PPHN is often complicated by parenchymal lung injury, such as meconium aspiration, pneumonia and surfactant deficiency, further compromising efforts to improve oxygenation.

When other therapies fail neonates are treated with extracorporeal membrane oxygenation.[7] This therapy improves survival in neonates with respiratory failure, but its administration is labor-intensive and costly and necessitates large amounts of blood products. The mortality rate in neonates treated with extracorporeal membrane oxygenation is 15-20 percent and 10-20 percent of the neonates, whose survive have substantial developmental delay.[8] Effective treatment has been limited by the absence of a selective pulmonary vasodilators. Intra-venous vasodilator agents can cause non-selective vasodilation, resulting in worsening of intrapulmonary shunting and systemic Hypotension.[9] Neonates with PPHN might be hypoxemic from a combination of intrapulmonary shunting secondary to parenchymal lung disease and extrapulmonary shunting secondary to increased pulmonary vascular resistance with or without myocardial dysfunction. INO (Fig. 18.2) acutely improves oxygenation in most-term and near term neonates by reversal of extrapulmonary right to left shunting of blood secondary to pulmonary vasodilation and also improves VQ matching secondary to redistribution of pulmonary blood flow to well ventilated lung regions.[4,5]

Clinical trials indicate that need for ECMO is diminished by INO[10] (Fig. 18.3). Responsiveness to INO in these patients is dependent on the primary disease or physiologic cause of hypoxemia, with the best response rates observed in patients with idiopathic PPHN.[11] In neonates with severe parenchymal lung disease, responsiveness to INO can be improved by therapies that enhance lung recruitment, especially during high frequency

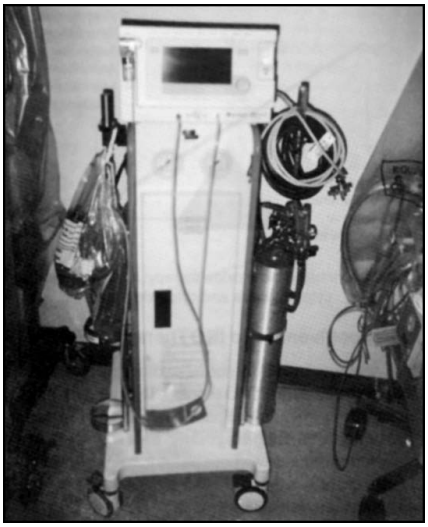

Fig. 18.2: Nitric oxide delivery system

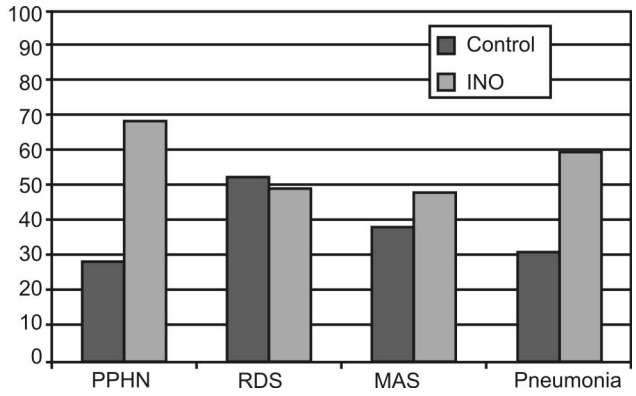

Fig. 18.3: Percent survival without ECMO by disease category in a controlled trial of INO occurred in newborns with PPHN or pneumonia RDS–Respiratory distress syndrome. MAS–Meconium aspiration syndrome, PPHN–Primary pulmonary hypertension

(Source: Neonatal inhaled Nitric Oxide study group)

oscillatory ventilation (HFOV). The combination of HFOV and INO can be efficacious in patients who fail to respond to either therapy alone.[12]

Doses

Experimental data support the notion that the minimally effective doses of INO should be used. At high concentrations INO can react with oxygen to form dioxygen nitrite (NOO), which has been shown to cause surfactant destruction.

The recommended dose is 10 to 20 part per million (ppm).[10,13] When dose is increased to 80 ppm, if the improvement in PaO_2 was less than 20 mmHg, increased incidence of methemoglobinemia occurs without any increase in PaO_2.[14] At the same time administration of a subtherapeutic (2 ppm) dose of INO may adversely affect the clinical response to a subsequent therapeutic doses of INO.[15] Clark et al used INO at 20 ppm for 24 hours followed by 5 ppm for next 96 hours and requirement for subsequent ECMO was reduced.[16] Figure 18.1 shows the nitric oxide delivery setup with dial regulator of PPM dose of INO.

Duration of Treatment

No controlled data are available to determine the maximal safe duration of INO therapy. In multicenterclinical trials of INO, the typical duration of INO has been less than 5 days, which parallels the clinical resolution of PPHN, [16] If INO is required for longer than 5 days, other causes like pulmonary hypoplasia must be excluded. INO can be discontinued if the fraction of inspired oxygen is less than 0.6 and PaO_2 is more than 60 without evidence of rebound pulmonary hypertension or an increase in FiO_2 more than 15 percent after INO withdrawal.[13]

Weaning

Sudden withdrawal can be associated with life-threatening elevation of pulmonary vascular resistance, profound desaturation and systemic hypotension caused by decreased cardiac output. Exogenous NO may down regulate endogenous NO production, which contribute to severity of pulmonary hypertension after INO withdrawal. To avoid these rebound effects numerous approaches have been used and INO should be reduced in a step wise fashion.[17]

Unresponsiveness to INO Therapy in PPHN

Many neonates have only partial or transient improvement in oxygenation during INO therapy. INO tends to increase PaO_2 more readily in idiopathic PPHN than in patients with congenital diaphragmatic hernia.[17] Its use in hypoxemic neonates without pulmonary hypertension.

Unresponsiveness to INO[18] is commonly seen in following situations:

1. INO use in hypoxemic neonates without pulmonary hypertension.
2. Inability to deliver NO due to poor lung inflation.
3. Unsuspected or missed anatomic cardiovascular lesions.
4. Alveolar capillary dysplasia is a very rare cause for PPHN and is characterized by a developmental abnormality in the pulmonary vasculature. Despite aggressive therapy with NO and ECMO survival is rare.[19]
5. Advanced vascular remodeling or severe lung hypoplasia.

In some cases, INO therapy reverses right to left shunting but hypoxemia may persist due to intrapulmonary shunt, suggesting underlying disease. In these situations changes in conventional ventilator management or HFOV can further improve PaO_2 by improving lung

inflation and may decrease the need for ECMO.[11] In many cases greater improvement is achieved with INO in combination with either therapy alone.[19]

Monitoring

Methemoglobinemia occurs after exposure to high concentration of INO. This complication has not been reported at lower doses. However, because methemoglobin reductase deficiency may occur unpredictably, it is reasonable to measure methemoglobin level by co-oximetry within four hours of starting INO therapy and subsequently at 24 hours intervals.

Transport with INO

Although INO therapy is often effective, 30-40 percent of sick newborns do not have sustained improvement in oxygenation and hemodynamics after the initiation of therapy often require transport to ECMO center. Abrupt discontinuation may be dangerous and availability of NO during transport is vital.

Long-term outcomes of neonates treated by INO has been studied widely, preliminary studies show no excess adverse health or neuro-developmental outcome among PPHN survivors treated with NO compared with those treated with conventional therapies.[20]

The premature newborns-uncertainties about use of INO.[21]

In the preterm neonate, severe respiratory failure is, in large part, the result of surfactant deficiency. Although treatment with exogenous surfactant can cause dramatic improvements in oxygenation. Some have suboptimal responses. Low dose INO causes immediate improvement in oxygenation in preterms.[22] It may be effective as a lung specific anti-inflammatory therapy to decrease lung neutrophil accumulation and the associated inflammatory injury and subsequent decreased incidence of chronic lung disease. INO is shown to impair platelet function in vitro, but clinical trials have not shown increased incidence of ICH,[23] and a trend in the reduced risk and severity of chronic lung disease among INO treated prematures is the main working hypothesis for most of the ongoing trials.[24]

INO in Chronic Lung Disease

Long-term ambulatory use of NO via nasal canula causes decrease in PVR and improved oxygenation in adults with stable chronic obstructive pulmonary disease. Its efficacy is not proved in interstitial pulmonary fibrosis, although transient improvement occurs. It can cause bronchodilation, but not as effectively as beta agonists.[25]

INO Therapy in Children with ARDS

The management of ARDS continues to be a challenge. Clinically ARDS is characterized by pulmonary hypertension and profound hypoxemia, abnormal vasoreactivity and increased permeability. Unlike PPHN

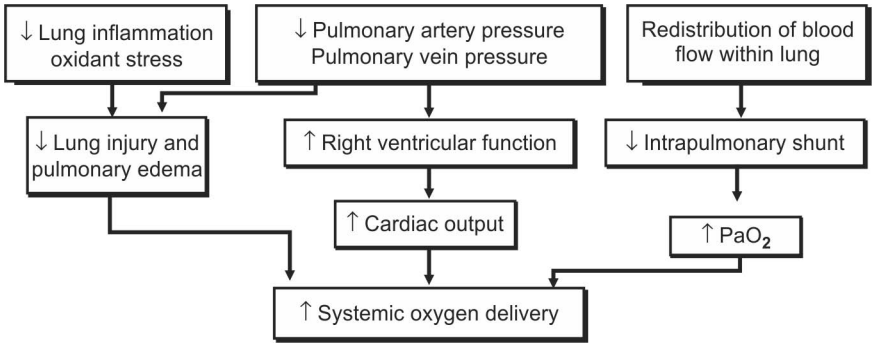

Fig. 18.4: Physiological targets of inhaled nitric oxide therapy in acute respiratory distress

extrapulmonary shunt does not occur in ARDS and hypoxemia is primarily due to intrapulmonary shunt (perfusion of lung units that lack ventilation). When pulmonary hypertension in ARDS is profound, right ventricular contractility may be depressed and its subsequent dilation may interfere with left ventricular function which further aggravates gas exchange.[26]

Physiological Effects of INO in ARDS (Fig. 18.4)

1. INO lowers pulmonary artery pressure and pulmonary vascular resistance.
2. Decreases V / Q mismatch-The low dose INO redirects blood flow from poorly aerated, atelectatic or diseased lung regions to better aerated distal air spaces. This is known as "microselective effects". This response is dose related, lower doses achieving greater oxygenation. At higher doses this microselective effect is lost and NO may reach poorly ventilated lung areas.[27]
3. INO decreases lung inflammation, vascular permeability and thrombosis, thus reduces permeability edema formation, although some studies suggest that it can inactivate surfactant.[26,27]
4. Permissive hypercapnia (a strategy used in management of ARDS as an attempt to decrease ventilator induced lung injury caused by barotrauma or volutrauma. Tidal volume and minute ventilation are decreased and $PaCO_2$ allowed to rise. Hypercapnia exacerbates pulmonary vasoconstriction. INO attenuates this and allows use of permissive hypercapnia.[28]

ARDS Controversies with INO Therapy

Despite wonderful physiologic effects, it remains unproven, whether improved oxygenation in ARDS are simply cosmetic or actually beneficial in terms of mortality.[29] Various studies report acute improvement in oxygenation but fail to alter mortality, ventilator days and other critical end points. Actually ARDS is a clinical syndrome with multiple complicating factors, such as sepsis and multiorgan dysfunction. Moses

prospective controlled studies using large patient population are needed to document any outcome benefits of INO therapy in ARDS.[30]

INO in Cardiology

Pulmonary hypertension with associated right ventricular dysfunction may complicate postoperative cardiac patients despite maximal pharmacologic and ventilatory support. By reducing mean pulmonary artery pressure, INO may protect the right ventricle, while maintaining left ventricular filling by increasing pulmonary arterial blood flow.[31]

Congenital Heart Disease

The use of INO has been shown to be helpful for the assessment of pulmonary vascular reactivity in selecting patients for surgery and postoperative management.[32] Post-cardiac surgery pulmonary has been successfully treated with INO in patients with significant prospective pulmonary hypertension.

Primary Pulmonary Hypertension

INO is used to test pulmonary vascular reactivity. A positive response with decrease in pulmonary artery pressure suggests a favorable response to long-term vasodilator therapy with prostacyclin or calcium channel blockers.

Miscellaneous Uses and Ongoing Trials

1. *Life-threatening status asthmaticus:* In children with life-threatening asthma, hypercapnea increases pulmonary vascular tone, thus increasing right ventricular afterload, which is already compromised by positive pressure ventilation and air trapping. NO plays an important role in regulating bronchial smooth muscle tone. Selective vasodilation of ventilated lung units may improve oxygenation and carbon dioxide elimination and unload the right ventricle, improving cardiac output.[33]
2. *Cerebral malaria:* Some researchers have used it, but prospective multicenter trials and are needed to document beneficial effects.[34]
3. *Heart transplantation:* INO is a useful adjunct to the postoperative treatment protocol of heart transplant patients with pulmonary hypertension. It selectively reduces PVR and enhances right ventricular stroke work.[35]
4. *Lung transplantation:* Reperfusion injury is a major cause of mortality and morbidity among lung transplant recipients. Prophylactic INO does not prevent reperfusion injury in human lung transplantation however, if started at reperfusion, improves gas exchange and reduces pulmonary artery pressure in those patients who develop reperfusion injury.[36]
5. *Acute myocardial infarction (AMI):* Given the important role that NO plays in regulatory platelet activation, interest has arisen in developing technique for increasing NO donors in the setting of AMI.[37]

6. *Neonatal chronic lung disease:* Defined as the continuing need in preterm infants for supplemental inspired oxygen at 36 weeks postconceptional age. INO improves oxygenation in most infants with early chronic lung disease, without inducing changes in markers of inflammatory or oxidative injury.[38]

Adverse Effects of INO

1. *Rebound effects:* Abrupt withdrawal of nitric oxide can cause rebound pulmonary hypertension, right ventricular failure and severe hypoxemia.[39]
2. *Prolonged bleeding time:* INO increases platelet cyclic GMP and by inhibiting platelet aggregation can increase bleeding time. Although clinically signi-ficant bleeding is fortunately not observed.[40]
3. *Paradoxical worsening* of oxygenation in chronic lung disease.[41]
4. *Elevated pulmonary capillary wedge pressure:* In patients with left ventricular dysfunction and poor ventricular compliance, an increase in pulmonary flow can increase left ventricular filing pressure, leading to ventricular failure and pulmonary edema.[42]

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19 Chapter

Extracorporeal Membrane Oxygenation

Ramesh Sachdeva, Praveen Khilnani

Through extensive research and development in the area of cardiopulmonary bypass, machine-managed extracorporeal oxygenation of blood has greatly evolved. In 1937, the first attempt at extracorporeal oxygenation was made by the direct bubbling of oxygen gas into blood. These oxygenators caused severe hemolysis and protein denaturation, which was a result of the direct blood-gas interface. Thus, their use was limited to only a few hours.

In order to overcome this complication, use of a semipermeable membrane oxygenator was implemented. This prevented direct contact of blood and gas, and the concept of prolonged extracorporeal support was born. Clinical reports of long-term, membrane extracorporeal support of patients with respiratory failure were described in the early 1970s. By 1974, 150 adult patients with respiratory failure of diverse etiologies had undergone extracorporeal support. This led to a multicenter trial comparing extracorporeal membrane oxygenation (ECMO) vs conventional ventilation, which showed that early survival rates were unchanged. Therefore, ECMO as a treatment modality in adult respiratory failure did not gain universal popularity.

In the same period, however, neonates [especially those with persistent pulmonary hypertension of the newborn (PPHN)] had improvement in outcomes secondary to ECMO, although premature babies at less than 35 weeks gestation had an unacceptably high incidence of intracranial hemorrhage. Since then, ECMO, as a rescue treatment modality for infants over 35 weeks gestation and children, has grown and become increasingly popular in intensive care units. However, currently, use of ECMO is increasing in adults, pediatrics. With the use of HFOV, use of ECMO has somewhat declined in neonates. For postoperative support or primary cardiac support, use of ECMO continues to be frequent and increasing.

Indications and Outcomes

The most common indications among neonates include: PPHN, meconium aspiration, respiratory distress syndrome (RDS), congenital diaphragmatic hernia, pneumonia, sepsis, and idiopathic causes. These indications and their outcomes are summarized below in Tables 19.1 to 19.4.

ECMO is offered when conventional regimens are ineffective. For respiratory indication, infants with meconium aspiration syndrome have

TABLE 19.1: International summary as of January, 2002

Group	*Total reported*	*Number survived to discharge/ transfer*	*Survival*
Neonatal respiratory	16,941	13,198	78%
Neonatal cardiac	1,605	618	39%
Neonatal ECPR	71	30	42%
Pediatric respiratory	2,216	1,210	55%
Pediatric cardiac	2,281	929	41%
Pediatric ECPR	118	43	36%
Adult respiratory	721	370	51%
Adult cardiac	343	111	32%
Adult ECPR	69	22	32%
Total	**24,365**	**16,531**	**68%**

ECMO registry report of the Extracorporeal life support organization (ESLO), 2002.

TABLE 19.2: Neonatal respiratory case statistics—International summary as of January, 2002

Primary diagnosis	*Total*	*Number survived*	*Survival*
CDH	3,816	2,063	54%
MAS	5,976	5,612	94%
PPHN/PFC	2,471	1,943	79%
RDS/HMD	1,333	1,120	84%
Pneumonia/sepsis	2,475	1,828	66%
Air leak syndrome	87	60	69%
Others	985	652	66%

ECMO registry report of the Extracorporeal life support organization (ESLO), 2002.

TABLE 19.3: Pediatric respiratory case statistics—International summary as of January, 2002

Primary diagnosis	*Total*	*Number survived*	*Survival*
Bacterial pneumonia	228	118	52%
Viral pneumonia	622	381	61%
Aspiration	160	103	64%
Pneumocystis	17	7	41%
ARDS	288	155	54%
Other(s)	937	461	49%

ECMO registry report of the Extracorporeal life support organization (ESLO), 2002.

TABLE 19.4: Cardiac case statistics—International summary as of January, 2002

Primary diagnosis	*Total*	*Number survived*	*Survival*
Congenital defect	3,093	1,168	38%
Cardiac arrest	115	30	26%
Cardiogenic shock	115	49	43%
Myocarditis	122	73	60%
Cardiomyopathy	274	130	47%
Others	642	248	39%

ECMO registry report of the Extracorporeal life support organization (ESLO) 2002.

the best outcomes with survival rates of 94 percent; whereas, infants with congenital diaphragmatic hernia have lower survival rates (54%). Appropriateness of the therapy in older children remains uncertain.

ECMO is being increasingly used for cardiac support, as well. The most common use is on patients with intractable cardiac failure after cardiothoracic surgery,[1,2] but patient outcomes depend mainly on the etiology of the cardiac failure. Overall, there has been an increase in the number of these indications resulting in better outcomes, which is probably due to increased experience.[3]

Most recently, ECMO has been used as a tool for resuscitation on patients with cardiopulmonary arrest,[4-6] and some centers have used ECMO for support of donor abdominal organs.[7]

The prediction of mortality in pediatric patients is more difficult due to the coexistence of multiorgan failure. Matching for diagnosis and severity of illness, ECMO-treated patients had a 74 percent survival vs 51 percent survival in non-ECMO-treated patients.[8] This study shows that when used appropriately, survival in some patients is enhanced by ECMO. Survival has progressively improved as per ELSO 2009 data (Table 19.5).

TABLE 19.5: ELSO (Extracorporeal life support organization) Registry: 7/2009

Neonate	*Number of cases*	*Survival (%)*
Respiratory	23,191	85
Cardiac	3,749	59
Pediatric		
Respiratory	4,188	64
Cardiac	4,564	62
Adult		
Respiratory	1,663	60
Cardiac	1,059	48
Total	40,195	74

Patient Selection Criteria

Determining that a patient is unresponsive to "maximal medical therapy" and considering the use of ECMO remains difficult and controversial. Most criteria have evolved from the neonatal ECMO experience.[9,10]

TABLE 19.6: Criteria for ECMO

1. Alveolar-arterial oxygenation difference ($AaDO_2$):
   (Predicted Mortality greater than 80%)
   > 610 × 8 hr or > 605 × 4 hr if PIP > 38 cm H_2O
2. Oxygenation index (OI):
   OI > 40 predicted mortality > 80%
   OI > 25-40 predicted mortality 50-80%
3. Acute deterioration:
   PaO_2 < 40 mm Hg × 2 hr and/or pH < 7.15 × 2 hr
4. Unresponsiveness:
   PaO_2 < 55 mmHg and pH < 7.40 × 3 hr
5. Barotrauma (any 4 of 7 simultaneously):
   - Pneumothorax
   - Pneumopericardium
   - Pneumoperitoneum
   - Pulmonary interstitial emphysema
   - Persistent air leak > 24 hr
   - Mean airway pressure > 15 cm H_2O
   - Subcutaneous emphysema

Data adapted from Georgetown University Hospital Pediatric ECMO program, Washington DC, 1997.

TABLE 19.7: General eligibility criteria for ECMO

Ventilator support of < 7days duration
General ventilator setting:
– PIP > 35
– PEEP > 10
– Mean airway pressure > 18 cm H_2O
  OI > 40
  PaO_2 FiO_2 < 150
  Failure of other therapies:
  – Pressure limited, inverse-ratio ventilation
  – Surfactant
  – High-frequency ventilation
  – Permissive hypercapnia
  – Inhaled nitric oxide

Data adapted from Georgetown University Hospital Pediatric ECMO program, Washington DC, 1997.

Defining criteria that will predict mortality in infants using conventional therapy continues to be elusive. Common criteria for the selection of ECMO candidates are shown in Table 19.6. The general eligibility criteria for pediatric ECMO are shown in Table 19.7.

Technique

The two basic types of ECMO are venoarterial (VA) and venovenous (VV). This terminology describes the direction of blood flow. The outflow is always venous, but the inflow can be arterial (VA) or venous (VV). Outflow of blood

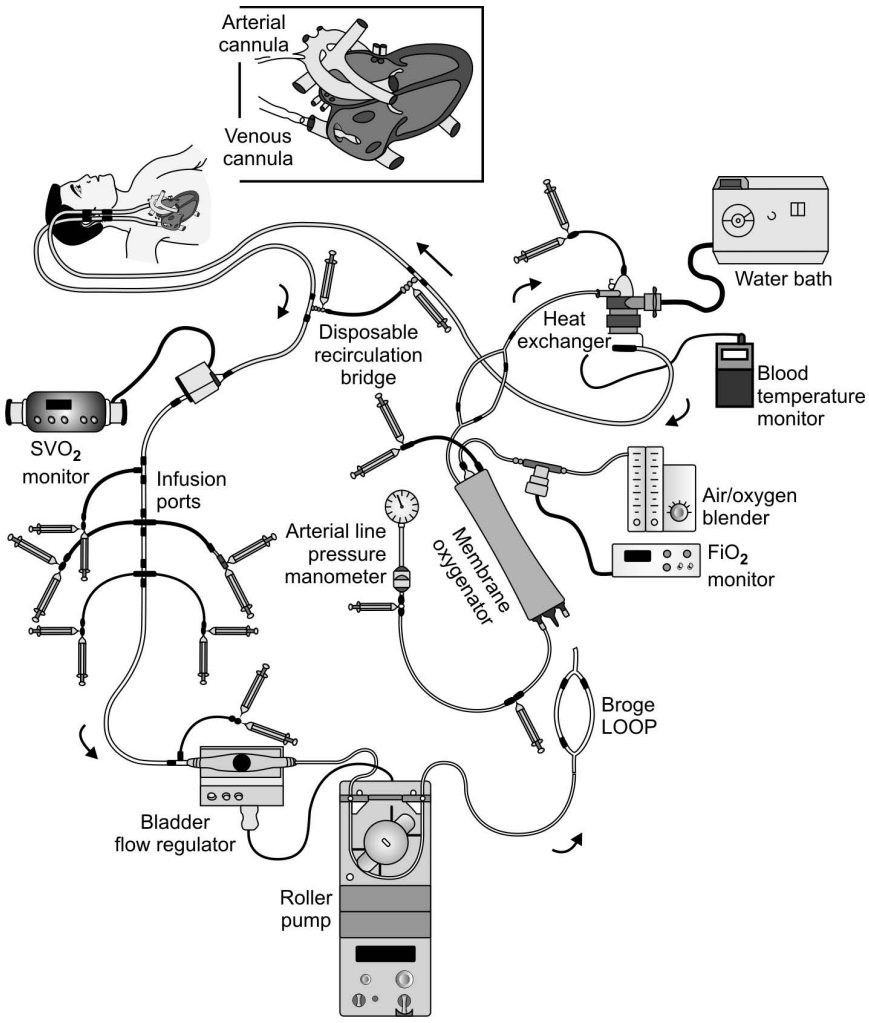

Fig. 19.1: ECMO circuit

in VA and VV ECMO is from the right atrium through a catheter placed through the right internal jugular vein. In older patients, other venous sites have been used. In VA mode, after oxygenation in the ECMO circuit, the blood is returned to the patient through an arterial cannula, which is placed in the ascending aorta through the right common carotid artery (Fig. 19.1). A cannula can also be placed directly into the right atrium and the aorta through a sternotomy.

Patients with profound left ventricular failure need a left atrial or ventricular catheter to obtain decompression of the left heart. The artery that was cannulated is permanently ligated. The effect of this is unknown.[11,12] Some centers have begun repairing the artery at decannulation.[13] Repairs had an early patency rate of 90 percent in some centers.[14]

Patients with normal cardiac function, as well as those with severe pulmonary disease, may be candidates for VV ECMO support (Table 19.8).

TABLE 19.8: Exclusion criteria for ECMO

Any one of the following underlying imminently fatal or irreversible disease states excludes the patient from ECMO:

1. Severe CNS injury or asphyxia
2. Persistent plasma lactate > 225 mg/dl (is highly predictive of death); (Note: > 135 mg/dl is highly predictive of adverse neurologic sequela in neonates)
3. Base deficit > 30 on 2 ABG's
4. Severe neurological exam persistent after respiratory and metabolic resuscitation
5. End-stage malignancies or advanced AIDS
6. Severe acquired or congenital immunodeficiency
7. Major burn
8. Advanced liver failure
9. Evidence of ongoing uncontrolled bleeding
   (A potentially correctable coagulopathy is not an exclusion).
10. Severe fibrosis on lung biopsy
11. Severe pulmonary disease ventilated aggressively for > 10 days
12. Lethal condition incompatible with long life, including trisomy 13 and 18

A double lumen venous cannula has been used in neonates, and in adults, the blood is returned to the distal iliac vein of the inferior vena cava. The blood first enters a small bladder that is attached to a servo-regulated box connected to a roller pump. Inadequate blood return triggers an alarm on the bladder box, which in turn, shuts the pump off. When the bladder refills, the pump restarts. This process prevents excessive negative pressure, which otherwise might result from a kinked cannula or hypovolemia, and more importantly, prohibits the formation of air bubbles.

After exiting the bladder, the blood is actively pumped by a roller pump into a membrane oxygenator. The oxygenator consists of a hollow silicon envelope placed inside a silicone sleeve. The blood flows on the outside of the coiled envelope, and the gas flows in a counter-current direction inside the membrane. The size of the membrane is chosen according to patient size. There is an effective gas exchange here. Next, the blood flows into a heat exchanger, and then, it is infused back into the patient. The ECMO circuit is designed with a bridge that allows the child and the circuit to be isolated from one another. The blood is heparinized, and the heparin effect is measured by activated clotting time (ACT), which is maintained at 180-220 seconds. ACT can be measured at the bedside.

ECMO Management

Cannulation is done at the bedside under deep sedation and neuromuscular blockade. An initial bolus of heparin (100-200 units) is given just prior to the cannulation, after which a heparin infusion is started and continued throughout the duration of the ECMO. The flow is initially started low by 50 ml/kg/min and gradually increased by 50 ml increments. Infants need 100-200 ml/kg/min for adequate perfusion and oxygenation, although there are patients who may need more. Pediatric patients usually need 90 ml/kg/min to achieve the same goals. In VA ECMO, as the flow is increased, the left ventricular output decreases, and the arterial waveform becomes less pulsatile.

Stored blood is used to prime the circuit, which may be acidotic and calcium depleted. Using THAM (tromethamine) or bicarbonate in the priming fluid can correct acidosis. It is also recommended to measure the electrolyte concentration of the stored blood. Patients will need intermittent blood products transfused. Fresh frozen plasma may be needed intermittently to replenish clotting factors. The ECMO circuit also sequesters platelets, and counts of 80,000-100,000 are maintained routinely.

Adequacy of nutrition is maintained by initiation of hyperalimentation, and early enteral feeds are not a contraindication. Diuretics may be needed to prevent fluid retention.

While on a ventilator, patients are placed on relatively non-traumatic settings to promote lung healing. A PIP of 18-25 mm H_2O, with a PEEP of 4-5 mm H_2O, is generally used at the Children's Hospital of Wisconsin. The ventilator rates are set at 6-12 breaths per minute and the FiO_2 is 25-30 percent. Sometimes, older children are managed with a PEEP of 10-12 to prevent loss of functional residual capacity.[15,16] Patients with barotrauma and air leak may benefit from high-frequency ventilation, in addition to ECMO. Typically, neonates benefit from low mean airway pressure and lung rest, and pediatric patients benefit from maintenance of functional residual capacity with higher PEEP.

When the underlying process improves, the patient is weaned to low ECMO flows (50-100 ml/kg/min) and optimal ventilator settings. A decision to decannulate is made after the patient maintains adequate oxygenation and perfusion in these settings for 2-4 hours. This weaning of flow can be achieved in slow reductions of flow rate by increments of 10-20 ml/kg/min every 1-2 hours, upto a flow rate of 50-100 ml/kg/min. During the process of weaning, blood gases and the mixed venous saturations should be frequently monitored. A more rapid weaning rate can be achieved by decreasing the flow in larger increments over shorter time intervals. Once a flow rate of 50-100 ml/kg/min has been achieved, the patient is monitored for a few hours. If deterioration is seen, high flow is re-established for 24 hours before a repeat trial is performed.

Continuous venovenous hemofiltration (CVVH) can be use during ECMO to remove fluids (Fig. 19.2) when fluid overload is a major problem.

Complications

Mechanical Complications

The most common mechanical problems are oxygenator failure, tubing rupture or leak, cannula kinking, power failure, air in the circuit, and accidental decannulation.

Patient Complications

Bleeding from heparinization is a common complication. Intracranial hemorrhage is catastrophic. At the Children's Hospital of Wisconsin, daily head ultrasounds are performed on infants with open fontanels. As any other site can be involved just as easily, a high index of suspicion is needed.

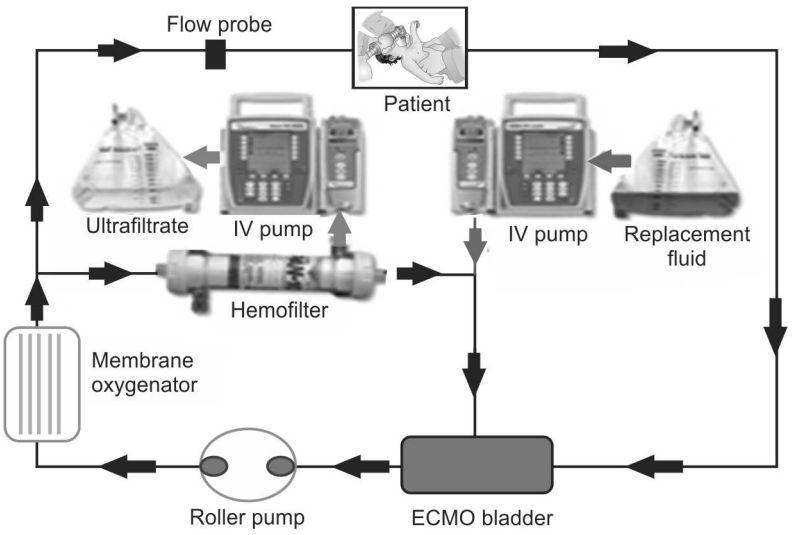

Fig. 19.2: CVVH (continuous venovenous hemofilteration loop) in ECMO circuit

Since infection is also problematic, daily surveillance cultures are ordered on all ECMO patients at the Children's Hospital of Wisconsin. Prophylactic antibiotics are not used to treat infection.

Embolization is another risk, especially with VA ECMO, and can consist of a clot, air, or particulate matter. At the Children's Hospital of Wisconsin, a bubble trap is added to the arterial side of the circuit in an attempt to reduce this risk. Sensorineural hearing loss is a long-term complication with a reported incidence rate as high as 24 percent.[17] Additionally, there is the possibility of catastrophic technical mishaps like catheter rupture, kinking of cannulae, power disruption, and accidental decannulation.

RECENT EVIDENCE ON USE OF ECMO

1. **Extracorporeal Membrane Oxygenation for 2009 Influenza A (H1N1) Acute Respiratory Distress Syndrome** Australia and New Zealand ECMO Influenza Investigators JAMA 2009;302:17 ELSO H1N1 Registry: 2010.
   Observational study from 6/1 - 8/31 2009. 68 adults were placed on ECMO for influenza related ARDS (61 H1N1, 7 suspected H1N1). 54/68 survived to "off ECMO" (~80%) there were no published comorbidities or follow-up .
2. **CESAR-Trial** Peek GJ, et al. Lancet 2009;374:1351-6.
   Randomized controlled trial of Adult ECMO versus standard management 766 patients were screened, 180 enrolled, 90 randomized to control and managed in local hospital. 90 were randomized to ECMO and transferred to Glenfield hospital for management. There was 16% survival advantage without severe disability in the ECMO group

(Mortality: 37% ECMO; 53% Conventional).

3. **ELSO registry 2010 data**
   Last 8 years numbers of patients on ECMO have increased
   43332 cases: overall 74% survival 64% Survival to discharge
   Of those cases Almost 50% were Neonates, 25% pediatric and 25% were adults.
   Of 25% pediatric cases Cardiac: 39% Neonates and 47% Pediatrics Resp cases 56%.

CONCLUSIONS

Presently, ECMO is viewed as an invasive procedure with significant risks, and should be used only after careful evaluation of risks / benefits and discussion with the family. However, it continues to represent an important support option in select critically ill infants and children. In the future, with increased experience, this procedure will become an even safer, more effective alternative to many less efficacious conventional therapies. Currently, in India high cost is the main limiting factor though technology and technical know how is available due to extensive cardiac surgical experience in tertiary centers for many years.

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20

Chapter

Commonly Available Ventilators

Praveen Khilnani

There are three fundamentally different modes of ventilation available in the pediatric intensive care unit (PICU) and the neonatal intensive care unit (NICU): "Pressure ventilators", "volume ventilators", and high frequency ventilators. They all serve to support adequate ventilation and oxygenation, but each has its own particular niche. There are different types of ventilators available in the market. It is obviously impossible to provide a detailed description of every ventilator in common use. These ventilators will be described with brief salient features. Author has no affiliation to any company or brand.

Volume Ventilators

Historically, volume ventilators (time cycled, volume regulated, volume limited) were used in anesthesia (a bellows of defined tidal volume pumped at a given rate) and as pediatric and adult intensive care evolved. Initially, these ventilators were not used in the NICU due to the difficulty achieving consistent small volumes (5-7 ml / kg in a 1200 gm infant). Current volume ventilators are able to deliver small volumes consistently. In the past, triggering was inconsistent and increased the work of breathing. The latest generation (Baercub,Vela, Draager, Siemens 300 and servo i) has resolved these problems. In the NICU their use has been primarily in large infants with chronic lung disease (partly because SIMV (Synchronized intermittent mandatory ventilation) was only available on volume ventilators until recently or preoperatively (a tradition likely related to familiarity of operating room assistants with volume ventilators). Their use in the acute NICU settings has extended into the micropremie population.

PROS: Stable minute ventilation with known tidal volume. Simpler models available for use outside hospital setting. Control or SIMV modes are available. Home ventilators currently available are typically, "volume ventilators".

CONS: Tidal volume is maintained at the expense of peak airway pressure. If lung compliance falls by 50 percent (i.e. Endotracheal tube, ETT slipping down right mainstem) then to maintain tidal volume, peak airway pressure doubles, possibly increasing the risk of volutrauma or barotrauma. Since these ventilators do not have constant flow, to breathe spontaneously the infant always has to trigger open a valve to allow airflow. Large leaks

around the ETT can be problematic due to difficulty maintaining tidal volume and "triggering" (patient cycling) of the ventilator causing frequent alarming.

Pressure Ventilators

These are the most frequently used ventilators in the NICU. Traditional "pressure ventilators" are constant flow, time cycled, pressure limited devices (Sechrist ventilator). Constant flow implies that there is a constant flow of gas past the top of the endotracheal tube. Pressure limited means that once the pre-set PIP has been reached, it is maintained for the duration of the inspiratory cycle. Time cycled implies that breaths are given at fixed intervals, independent of the infant's respiratory efforts. Newer "pressure ventilators" can sense infant's breaths and synchronize with them. There may be some added work of breathing due to the need to trigger breaths, this has been hard to quantify and remains controversial.

PROS: The constant flow permits the infant to easily take spontaneous breaths. Simple, reliable mechanical design. Pressure limitation prevents sudden changes in PIP (peak inspiratory pressure) as compliance changes (i.e. on a pressure ventilator if compliance falls by 50 percent, PIP does not change–though tidal volume drops, e.g. ETT slipping down right mainstem). Leak around the endotracheal tube is compensated in a pressure ventilator by achieving preset pressure with whatever volume it has to pump.

CONS: Variable tidal volume as lung compliance changes, Should lung compliance worsen then Vt (tidal volume) will drop (if the ETT plugs Vt drops to zero, but the ventilator does not sense it). Should compliance improve (following surfactant for example), this may result in over-distention. If the child is exhaling during a non-synchronized ventilator breath, then the breath is ineffective.

High Frequency Ventilators

This is a radical innovation in ventilator design. The rate in "high frequency" is the Hz (range 3-15 Hz) (i.e. 180-900 breaths per minute). Since the tidal volume generated by these ventilators approximates dead space, simple pulmonary mechanics are not applicable.

High Frequency Oscillatory Ventilation (HFOV)

(SensorMedics 31OOA) uses a piston with diaphragm unit which actively moves gas in and out of the lung. This type of ventilator requires a special non-complaint breathing circuit. Indications for use of high frequency ventilation are unclear but include:

1. Initial and subsequent ventilatory support in very low birth weight infant with respiratory distress syndrome.
2. Air leak (pneumothorax, pulmonary interstitial emphysema).
3. Failure of conventional ventilation [pre-ECMO (Extracorporeal membrane oxygenation) step] particularly in persistent pulmonary

hypertension of the new-born, meconium aspiration syndrome, pneumonia, and pulmonary hemorrhage.

4. To reduce the risk of volutrauma and barotrauma when conventional ventilator settings are very high.

PROS: May allow gas exchange when conventional ventilation has failed.

CONS: Unclear that which patients will respond and there is some risk involved in 'just trying". Switching ventilators on an unstable patient who is on conventional ventilation may result in clinical deterioration. The high airway pressures often seen with high frequency ventilation can be transmitted to the heart (particularly with compliant lungs) and result in impaired cardiac output requiring inotropes and/or volume boluses. HFOV makes turning patients, taking X-rays, or performing ultrasounds more complex due to the heavy, non-flexible tubing. Stopping HFOV for suctioning or administering nebulized medications may negate its benefit.

Specific Ventilators

Note: Each ventilator manufacturer has utilized specific names for mode functions of their specific machine that may not be identical with other machines. Generally speaking most manufacturers aspire for providing a universal ventilator for all age groups, not yet achieved, however with increased sophistication in technology, pulmonary graphics facility is now available in most modern ventilators. Each user should familiarize oneself with manual knobs or touch screen, to start and set up the ventilator, achieve the initial settings of modes (A/C Assist control, PRVC or SIMV), rate (frequency), FiO_2, tidal volume/PIP, PEEP, Pressure support, inspiratory time (or I:E ratio), flow rate as well as setting of various ranges of alarms.

VELA VENTILATOR: VIASYS HEALTH CARE (USA) (FIG. 20.1)

Features (as listed by the manufacturer)

Variable ventilation controls with integrated digital display for all controls and alarms with different color codes. Flashing display of controls available for any incompatible settings.

Front panel lock built into the control knob, to prevent accidental or unauthorized change of ventilation parameters.

Alpha-numerical window display for monitors, alarms, system messages and other informations.

Ventilator is self-contained with built-in turbine (Air Supply) to run the unit independently without any additional Air or Oxygen Pressure Source.

Ventilator operates from AC, Internal Battery or optional External Battery Source. Display indicates the Power Source and different color codes available to indicate the charge status of the batteries.

Internal battery pack is standard and it takes over the unit automatically during power failure 2 hours. Batteries charging (internal and external) is automatic when it is used on AC source.

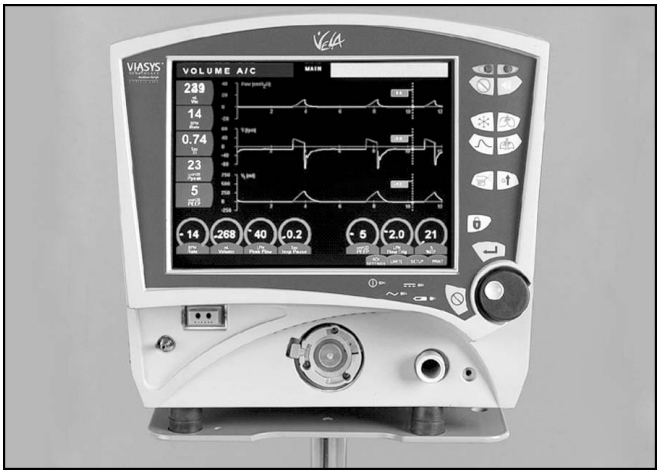


Fig. 20.1: VELA ventilator *(For color version see Plate 3)*

Basic machine has modes CMV, Assist CMV, SIMV and CPAP with independent Mode Selection Switches with PCV and Inspiratory Time. Peak flow ranges from 10-140 L / min for mechanical breath and upto 180 L / min for spontaneous breath. Flow Triggering is available along with bias flow settings ranging from 10-20 L / min. Pressure Support Ventilation is available in SIMV and CPAP modes. Inspiratory time range is 3.0–10 sec. Automatic flow calibration is available even when the ventilator is used on patient. Mechanical Over Pressure Relief valve is available as back up to High Pressure Limit Alarm for added safety to patient. Integrated nebulizer is available.

Monitored parameters include: Exhaled Tidal Volume, Spontaneous Exhaled Tidal Volume, Exhaled Minute Volume, Spontaneous Exhaled Minute Volume, PIP, MAP, PEEP, FiO_2, Total Breath Rate, I:E Ratio etc. Insp. Hold function is available for Static Lung Compliance measurement and display. Comprehensive Alarm package includes High Pressure, Low Pressure, Low Minute Volume, Low / High O_2 Inlet pressure, Apnea alarm and High breath rate.

Variable Apnea Back-up ventilation is available whenever Apnea is detected.

Ventilator works from 100-240 VAC and has a sound level less than 50 dB including built-in turbine.

NEONATAL VENTILATOR MODEL BEARCUB 750 PSV–VIASYS HEALTH CARE (USA) (FIG. 20.2)

Listed Features (from the manufacturer)

Microprocessor Controlled Time Cycle Pressure limited ventilator suitable for pre-mature babies, infant and neonates.

Ventilator have the following Modes of ventilation: Control, flow cycle assist control, SIMV / PSV, Flow-cycled SIMV, CPAP / PSV.

Fig. 20.2: Neonatal ventilator mode bearcub
(For color version see Plate 3)

Respiration Rate upto 150 bpm with inspiratory time for 0.1–3.0 sec, PEEP upto 30 cm H_2O, inspiratory pressure upto 72 cm H_2O.

It has integrated electronic blender for O_2 sets from 21-100 percent.

Selectable apnea alarm ranging from 5 to 30 sec with apnea backup ventilator whenever apnea is detected.

Safety features, viz. volume limit which the maximum tidal volume of all breaths delivered by ventilator (Range of volume limit 5–300 ml).

It is able to monitor following parameters: Breath rate, inspired and Expired Tidal Volume, Inspiratory time, expiratory time, I:E Ratio, peak inspiratory pressure, mean airway pressure, PEEP, percent of tube leak, Air / O_2 Pressure, Minute Volume.

Ventilator have comprehensive alarm package comprising of high breath rate, low PEEP / CPAP, low inspiratory pressure, volume limit, apnea alarm, flow sensor, high pressure limit, low gas supply, minute volume alarm.

It is state-of-art ventilator from reputed company with CE and ISO 9001 Certification.

VENTILATOR MODEL AVEA- VIASYS HEALTH CARE (USA) (FIG. 20.3)

Microprocessor controlled time cycle pressure limited ventilator is suitable for pre-mature babies, infant and neonates.

Ventilators have the following modes of ventilation: Control, flow cycle assist control, SIMV / PSV, Flow-cycled SIMV, CPAP / PSV.

Respiration Rate upto 150 bpm with inspiratory time for 0.1–3.0 sec, PEEP upto 30 cm H_2O, inspiratory pressure upto 72 cm H_2O.

It has integrated electronic blender for O_2 sets from 21-100 percent.

Selectable apnea alarm ranging from 5 to 30 seconds with apnea back-up ventilator whenever apnea is detected.

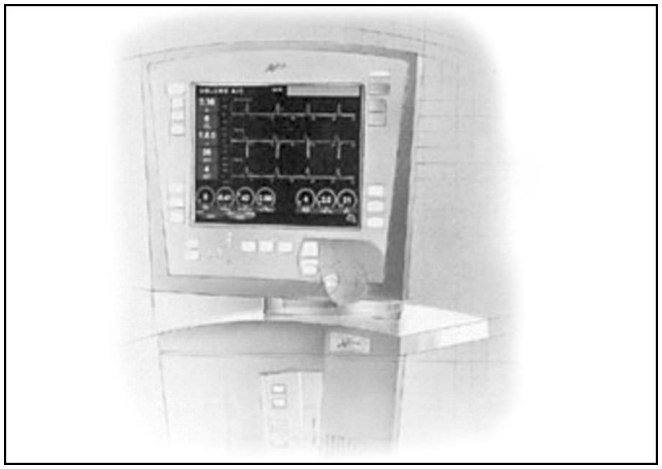


Fig. 20.3: Ventilator model AVEA
(For color version see Plate 4)

Safety features, viz. volume limit which limits the maximum tidal volume of all breaths delivered by ventilator (Range of volume limit 5–300 ml).

It is able to monitor following parameters: Breath rate, inspired and expired tidal volume, inspiratory time, expiratory time, I:E ratio, peak inspiratory pressure, mean airway pressure, PEEP, percent of tube leak, Air / O_2 pressure, minute volume.

Ventilators have comprehensive Alarm package comprising of high breath rate, low PEEP / CPAP, low inspiratory pressure, volume limit, apnea alarm, flow sensor, high pressure limit, low gas supply, minute volume alarm.

It is state-of-the-art ventilator from reputed company with CE & ISO 9001 certification.

DRAGER BABYLOG 8000 (FIG. 20.4)

This ventilator is specifically designed for infants up to 10 kilograms (22 pounds). It is capable of both volume and pressure ventilation. A flow sensor at the Y piece close to the patient accurately measures tidal volume and senses air flow initiated by the patient allowing triggering of the ventilator cycle. The sensor is able to compensate for small ETT leaks. High frequency ventilation can be delivered at 5-20 hertz.

The Drager Babylog 8000 provides the following modes: AC (assist control), SIMV PSV (pressure support ventilation), volume guarantee (VG), and independent expiratory flow. VG is often used with SIMV, PS and AC. The most important commonly used modes are SIMV, PSV, VG and CPAP (continuous positive airway pressure). This ventilator can also be used for non-invasive ventilation.

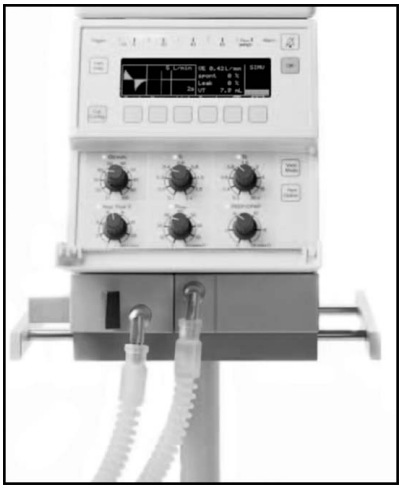


Fig. 20.4: Drager Babylog 8000
(For color version see Plate 4)

Drager Babylog 8000 Controls (as listed by the manufacturer)
Conventional ventilation, continuous flow, pressure-limited, time-cycled
Triggered ventilation SIMV, SIPPV, PSV1), leak adapted
- Trigger Flow/volume trigger, leak adapted
- Trigger delay approx. 40-60 ms

High Frequency Ventilation1) CPAP+HFV, IMV+HFV
- Frequency 5 to 20 Hz

Volume Guarantee Ventilation1) SIMV+VG, SIPPV+VG, PSV+VG
Oxygen mixer loss (bleed flow) 0 (zero) L/min
Settings
Inspiratory oxygen concentration 21-100 vol. percent oxygen
Peak inspiratory pressure 10 to 80 mbar
PEEP/CPAP 0 to 25 mbar
Maximal frequency 200 bpm
Inspiratory time 0.1 to 2 seconds
Expiratory time 0.2 to 30 seconds
Inspiratory flow 1 to 30 L/min
Base Flow (VIVE) 1 to 30 L/min
Monitoring
Flow monitoring at the Y-piece, integrated
Volume monitoring at the Y-piece, integrated
Lung function monitoring compliance, resistance C20/C
Method linear regression analysis
FiO_2 monitoring integrated
Real-time curves Flow and pressure, integrated
Inspiratory oxygen concentration 21-100 vol. percent oxygen
Peak pressure to 99 mbar
Mean airway pressure to 99 mbar
Graphic trends 6 parameters, integrated
Logbook record of up to 100 alarms
Notes: 1) optional available

Fig. 20.5: Drager babylog 8000 plus
(For color version see Plate 4)

Drager Babylog 8000 Plus, Evita XL, Evita 2 Dura (Fig. 20.5)

The Babylog 8000 plus is designed for harmonious ventilation of small children and the smallest pre-term babies. It has an advanced upgrade platform that has allowed it to keep pace with all new forms of treatment and clinical advances. Sensitive synchronization with gentle but precise support for spontaneous breathing reduces the work of breathing and makes the ventilation process much more comfortable for patients. All of the above features of Babylog 8000 are available in Babylog plus.

Drager Evita XL is a newer model useful for pediatric, neonatal as well as adult age groups. The Drager Evita 2 Dura Ventilator is used for adult and pediatric patients. Options include DC monitoring plus, ventilation plus, neo flow. Its features include modes such as, Invasive - Volume-controlled modes assist/control - SIMV PSV - MMV and Pressure-controlled modes, assist/control SIMV (PSV), CPAP, BIPAP1 /PCV.

SIEMENS SERVO 900C VENTILATOR (FIG. 20.6)

It is either a volume or pressure ventilator, no gas flow from ventilator between breaths. It is volume ventilator with IMV, SIMV, AC and pressure modes PC/PS. It has pediatric settings for alarm limits, but no specific infant modes. It is used when primarily volume ventilator needed in larger term infant and often for home ventilatory support. Currently, used only in the adult ICU. However, the servo ventilator 900C can be used in intensive care and patient transportation, for adults, and older pediatric patients.

Volume control: In volume controlled ventilation, the inspiratory flow is kept constant as preset by the Servo control System. As a result, the tidal volume is also delivered as preset, and inspiratory time and pause time are maintained as preset.

Pressure control—efficient ventilation with low pressure.

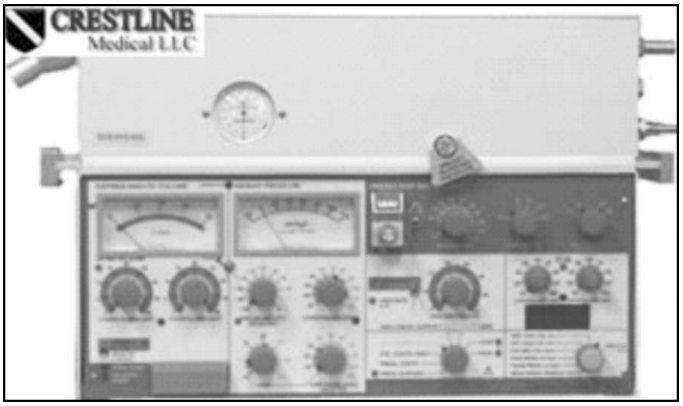


Fig. 20.6: Siemens servo 900C ventilator
(For color version see Plate 5)

Pressure control is a unique mode of the servoventilator. By maintaining preset airway pressure constant throughout the entire inspiratory period, the servo ventilator delivers the tidal volume using a lower pressure level than traditional controlled ventilation.

Pressure control ventilation with constant inspiratory pressure gives you a decelerating flow with the major part of the tidal volume delivered in the beginning of the inspiration and this prolonged time for gas exchange in the alveoli keeps lungs open with Pressure Control and Inverse I:E ratio.

Pressure controlled ventilation together with inverse I:E ratio is used to improve gas exchange and to prevent alveoli from collapsing during expiration. Using the inspiration time and pause time controls, the I:E ratio can be set from 1:4 to 4:1.

Siemens Servo 300/300A Ventilator (Fig. 20.7)

It can be used as a volume or pressure ventilator, with a low bias flow from ventilator between breaths. It does not have continuous high flow through circuit and requires some effort on the part of the infant to trigger significant flow. In the Neonatal Mode, there is a low continuous flow of 0.5 LPM through the circuit. A disruption of change in this flow caused by the infant's breathing is required to initiate / trigger an assisted breath. The major advantage over Siemens 900C is that it has infant ranges for Vt, flow, pressures, and alarms. It has extensive list of modes:
PC, VC, SIMV-VC+PS, SIMV-PC+PS, CPAP and PRVC (pressure regulated volume control). Uses include: (1) volume ventilation of small infants, (2) synchronized / mixed modes, (3) overcoming resistance of circuit and ETT with PS, (4) facilitation of weaning by allowing gradual entertainment.

The servo ventilator 300 offers a wide range of ventilation modes for supported and controlled ventilation. It offers modes like PRVC (pressure regulated volume control) and VS (volume support) to deliver the required volume at the lowest pressure. Preset ranges for all relevant flow and

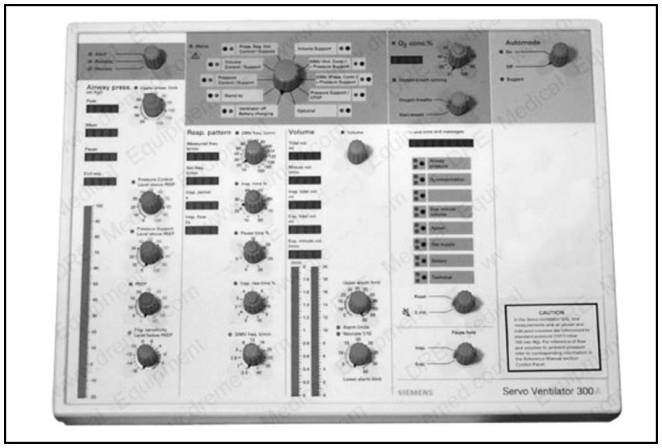


Fig. 20.7: Siemens servo 300/300A ventilator
(For color version see Plate 5)

volume parameters are automatically adjusted with a patient range selection knob. The servo ventilator 300 offers a wide range of ventilation modes for supported and controlled ventilation. The flow range covers very low flows from 0.1 ml / sec up to high flows of 3 L / sec.

Seimens Servo ventilator 300A is an improved version of Servo 300 ventilator.

SECHRIST VENTILATOR (OLD AND NEWER VERSIONS) (FIGS 20.8 AND 20.9)

This is continuous flow a pressure cycled time cycled ventilator. It has been commonly used for neonates with standard CPAP availability. Newer models are becoming available. The greatest advantage is absence of a demand valve to trigger ventilator cycle. Pressure support is not available in older models.

Fig. 20.8: Sechrist ventilator Old
(For color version see Plate 5)

Fig. 20.9: Sechrist ventilator new
(For color version see Plate 6)

VIP BIRD VENTILATORS (FIG. 20.10)

Fig. 20.10: VIP bird ventilator
(For color version see Plate 6)

Probably the earliest air driven ventilator with magnetic technology. Newer models have turbine technology alleviating the need for an air compressor to drive the ventilator. All modes are available for pediatric patients and small infants. A transport ventilator (BIRD AVIAN) is also available.

TRANSPORT VENTILATOR (BIRD AVIAN) (FIG. 20.11)

Fig. 20.11: Transport ventilator
(For color version see Plate 6)

NEWPORT VENTILATORS: E LOOM, BREEZE E150 AND WAVE E120 VENTILATORS (FIG. 20.12)

A relatively small size is the greatest advantage in being used as a transport ventilator. Delivers versatility, value and performance according to the manufacturer. It can be cheaper to use in the PICU.

The Newport El00 M is designed to deliver reliability and versatility. It is ideal for most patient applications, eliminating the need for and expenses of age specific or application limited equipment. New advances, such as Advanced Trigger Control and Auto-Set alarms, simplify the set-up and management of the ventilator. Duo Flow PLUS system allows to

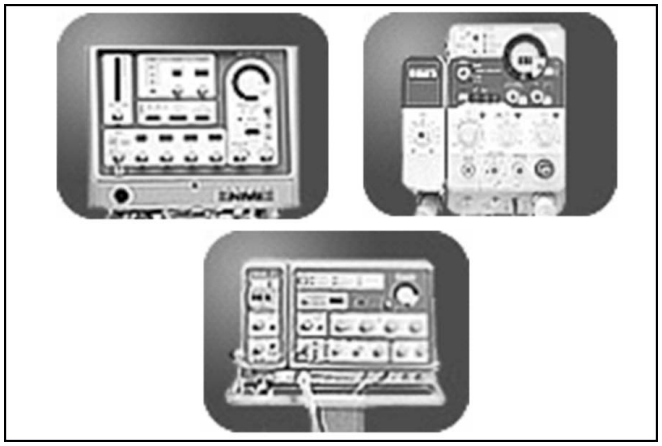
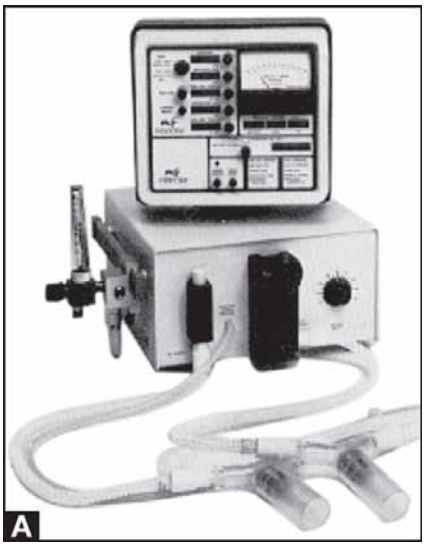


Fig. 20.12: Newport E 100M, Newport Breeze E 150, Newport Wave E120, Newport E 100M ventilator *(For color version see Plate 7)*

improve comfort, synchrony and work of breathing for spontaneously breathing patients.

These ventilators are available for pediatric intensive care unit, providing standard pressure, volume and time cycled nodes. PS is available, a unique flow triggering mechanism (bias flow and flow sensing) reduces work of breathing of a small child or infant making triggering easier.

INFANT STAR 500/950 VENTILATOR SYSTEM (FIGS 20.13A AND B)



Figs 20.13A and B: Infant star 500/950 ventilator
(Fig. 20.13B, for color version see Plate 7)

The infant Star 500 and 950 ventilators are timed cycled, pressure limited, continuous flow ventilators, offering adjustable background flow in the CPAP and IMV modes. The infant Star ventilators are designed to provide continuous ventilatory support for neonatal and pediatric patients less than 40 lbs (18 kg), with an adjustable flow rate range of 4 to 40 liters per minute (L / min), and background flow range of 2 to 30 L / min.

Infrasonics Infant Star 950 is a high frequency ventilator with star cart. It has a flow interruptor for delivering high frequencies.The 950 Ventilator is timed cycled, pressure limited, continuous flow ventilators, offering adjustable background flow in the CPAP and IMV modes. Operations in the CPAP and IMV modes are identical in the 500 and 950 ventilators.

SIEMENS SERVO-I (MAQUET) (FIG. 20.14)

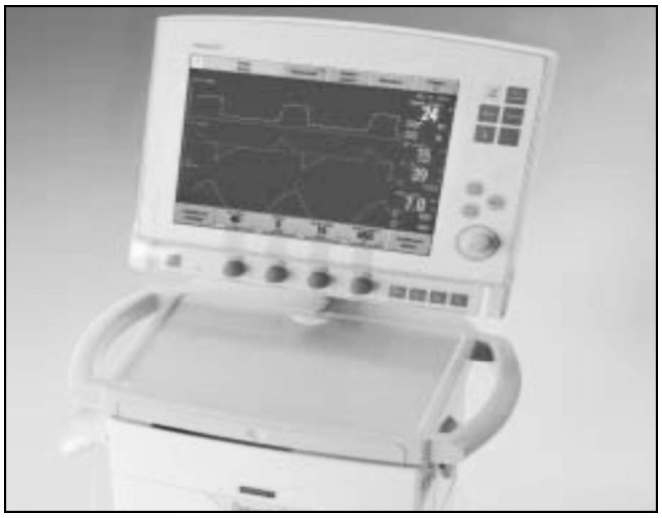


Fig. 20.14: Siemens servo *(For color version see Plate 8)*

Listed Features (from the manufacturer)

Supports neonatal and pediatric patients through multiple ventilation modes and sensitive triggering responses. Sensitive triggering and fast response times are important in preventing very young patients from "fighting the machine" and to ensure the delivery of safe, comfortable volumes. The pressure support mode of servo-I infant reduces the work of breathing and responds instantly to the child's changing needs. Treatment parameters and ranges can be flexibly customized and are automatically set, even when changing from one mode to another. The system can be upgraded to servo-I universal standard for all patient categories.

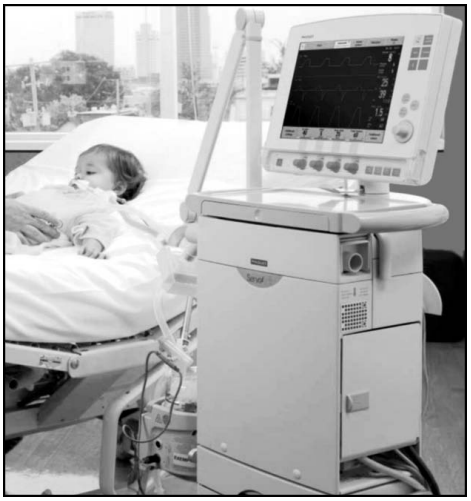


Fig. 20.15: Servo-i infant (Maquet)
(For color version see Plate 8)

Product Benefits

- Automode for fully adaptive patient interaction.
- Lung recruitment for an even wider perspective of ventilation.
- Methodology and modes: the ability to explore different treatment strategies.
- Transportation with no loss of treatment quality.
- New generation of ventilators.

SERVO-I INFANT (MAQUET) (FIG. 20.15)

TECHNICAL SPECIFICATIONS
Parameter settings
Inspiratory tidal volume (ml): 5 – 350 *(Optional – together with volume related ventilation modes)*
Inspiratory minute volume (l/min):0.3 – 20 *(Optional – together with volume related ventilation modes)*
Apnea, time to alarm (s): 5 – 45
Automode Trigger timeout (s): 3 – 7
Pressure level (cm H_2O): 0 – (80 – PEEP)
PEEP (cm H_2O): 0 – 50
PEEP in NIV (cm H_2O): 2 – 20
CPAP pressure (cm H_2O): 2 – 20
CMV frequency (breaths/min): 4 – 150
SIMV frequency (breaths/min): 1 – 60
Breath cycle time, SIMV (s): 0.5 – 15
PHigh (cm H_2O): (PEEP +1) – 50
THigh (s): 0.2 – 10
TPEEP (s): 0.2 – 10

PS above PHigh (cm H_2O): 0 – (80 - PHigh)
PS above PEEP (cm H_2O): 0 – (80 - PEEP)
PS above PEEP in NIV(cm H_2O):0 – (32 - PEEP)
Back-up pressure above PEEP (cm H_2O):5 – (80 - PEEP)
NIV Back-up rate (breaths/min): 4 – 40
O_2 concentration (%): 21 – 100
I:E Ratio: 1:10 – 4:1
T Insp. (s): 0.1 – 5
NIV Back-up TInsp (s): 0.3 – 1
TPause (s) 0 – 1.5
TPause (% of breath cycle time): 0 – 30
Flow trigger sensitivity level
(fraction of bias flow):0 – 100%
Press. trigg sensitivity (cm H_2O): 20 – 0
Insp. rise time (% of breath cycle time):0 – 20
Insp. rise time (s): 0 – 0.2
Insp. cycle off (% of peak flow): 1 – 70
Insp. cycle off in NIV (% of peak flow): 10 – 70
Nebulizer time (min): 5 – 30
Parameter: Setting range
Oxygen breaths: 100 percent for 1 minute
Start breath: Initiation of 1 breath (In SIMV mode
initiation of 1 mandatory breath)
Pause hold: Insp. or exp. (0 – 30 seconds)
Alarm silence/reset: 2 minute silence and reset of latched alarms
Compliance compensation: On/Off
Automode (optional): Automode On/Off
Servo Ultra Nebulizer (optional): Nebulizer On/Off

Suction Support
Pre oxygenation time: Max. 2 min
Post oxygenation time: Max. 1 min
Suction phase time: No maximum level
Adjustable oxygen level: 21 – 100 percent

Saving of data
Recording of current waveform and parameter values:
20 seconds of data will be recorded
(10 seconds before activated key and 10 seconds after). Serial port: RS-232C - isolated. For data
communication via the Communication Interface Emulator (CIE).
Network connection (optional): MIB (Medical Information Bus) monitorconnection
Data transfer Via Ventilation Record Card
Screen picture transfer: Via Ventilation Record Card

SENSORMEDICS 3100A OSCILLATOR (FIG. 20.16)

It is high frequency oscillatory ventilator (HFOV) with active inhalation / exhalation driven by a moving piston and diaphragm.

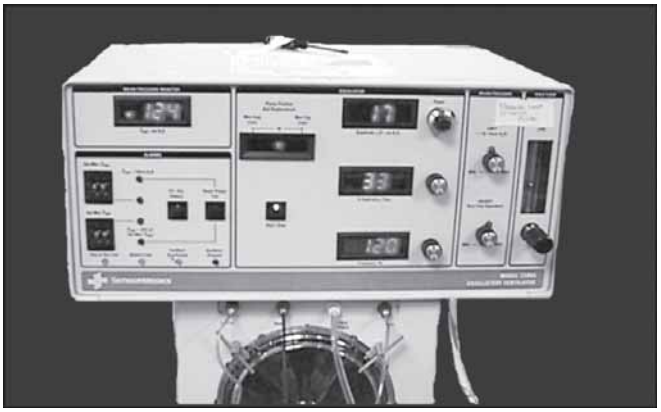


Fig. 20.16: Sensormedics 3100A
(For color version see Plate 9)

The Sensormedics 3100A High Frequency Oscillatory Ventilator was first approved for use in 1991 and is the only HFV approved for early intervention in the treatement of neonatal respiratory failure. The scope of application was broadened in 1995 to include selected pediatric patients failing conventional mechanical ventilation. The 3100A provides the ultimate in lung protection by inflating the lung with a continuous distending pressure and superimposing very small pressure and volume swings. Numerous publications, including clinical, animal and bench studies have reported improved benefits and outcomes asociated with the use of HFOV. There are over 3500 Sensor Medics High Frequency Oscillatory Ventilators in use worldwide today (Fig. 20.17). The 3100A is

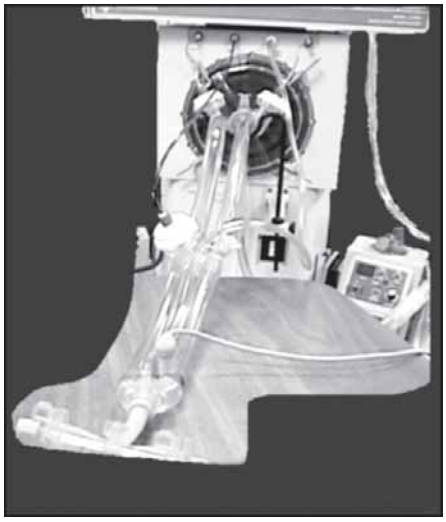


Fig. 20.17: Sensor medics high frequency oscillatory ventilators *(For color version see Plate 9)*

the standard of care in more than 90 percent of Level III nurseries and 75 percent of the Pediatric Intensive Care Units in the US.

It requires special stiff non-complaint ventilator circuit. It can be utilized for a wide weight range of infants. Some preliminary work using it in smaller infants suggests that it may result in less barotrauma than conventional ventilation. It is used extensively in western countries in severe Acute respiratory distress syndrome and meconium aspiration to avert the need for ECMO (See Chapter on High Frequency Ventilation).

RESPIRONICS BIPAP AND NON-INVASIVE VENTILATOR (FIG. 20.18)

Fig. 20.18: Respironics BIPAP
(For color version see Plate 9)

A portable convenient device that can be used for non-invasive ventilation in the PICU.Circuit is supplied with various sizes of masks for pediatric use.Ventilator is capable of delivering, iPAP, ePAP and pressure supported breaths, shorter weaning times and increased patient comfort. Many brands of NIPPV are available.

THE SLE 2000 FOR INFANT VENTILATION (FIG. 20.19)

The SLE 2000 is specifically designed for neonatal and infant patients. It allows the user to deliver conventional ventilation, i.e. CPAP, CMV, PTV or SIMV. It can also be used for nasal CPAP. Pneumatic performance is further enhanced by the patented valveless system.

- The operation of the unique valveless system eliminates the need for exhalation valves, diaphragms, etc. meaning less to clean and easier assembly
- The simple patient circuit, together with the valveless system, reduces problems of resistance and compliance
- The principle of operation of the valveless system eliminates inadvertent PEEP, and aids in the total clearance of expired gases
- Automatic gas flow adjustment
- Ability to maintain pressure waveforms at all rates

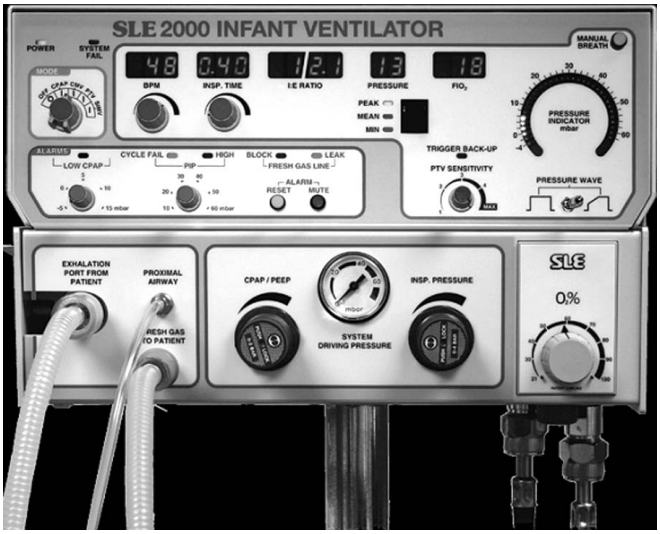


Fig. 20.19: The SLE 2000

- Sensitive airway pressure trigger
- Comprehensive alarm system
- Built in oxygen analyzer with continuous digital readout
- Clear and easily set controls
- High pressure dump on alarm
- Exhaled gases can be filtered
- Tamper-proof pneumatic controls
- Optional auxiliary blended flow outlet
- Choice of square or slow rise time, switch selectable
- Ability to use other gases, e.g. Nitric Oxide
- Easy to clean.

Technical Specification

Alarms
CPAP: Visual and intermittent audible
PIP / Cycle Fail / Low: Visual and intermittent audible
Fresh Gas Block or Leak: Visual and continuous audible
Loss of Mains supply: Battery powered, audible
Loss of Air or O_2 supply: Pneumatic, audible from blender
System Fail: Visual and intermittent audible

Supplies, Dimensions and Weights

Air and O_2: 3-5 bar
Voltage: 100-120 V 50 / 60 Hz
220-240 V 50 / 60 Hz
Power: 20 VA
Fuses: 100-120 V = T500 mA
220-240 V = T200 mA

Protection: Class 1 Type B
Size, ventilator only: 37 cm W × 31 cm H × 32 cm D
Height on pole: 137 cm
Weight, ventilator only: 10 kg
Complies with:
CE Declaration of Conformity
IEC 601-1 and 601-2-12 1988
BS 5724 Part 1 and section 2.12.1990
EMC Medical device 601-1-2

SLE 5000 (Fig. 20.20)

Features

Modes include: CPAP, CMV + TTV, PTV, PSV, SIMV + TTV + PSV, HFO, HFO + CMV

- Ability to preset parameters in all modes of operation
- Powerful HFO with *active* expiration to cover a wide range of patients
- Full color, total touch-screen operation
- Integral flow monitoring measuring lung mechanics and displaying of loops and waveforms
- Trending of measured parameters

Fig. 20.20: SLE 5000

- Standard patient circuit for all modes including HFO (except with NO therapy)
- Unique, patented valveless technology
- Integral battery with up to 60 minutes operating capability
- Software based, allowing for up grading to versions with new or improved functions.

Targeted Tidal Volume (TTV)

There is increasing clinical evidence to suggest, that it is volutrauma that causes lung injury, which is worsened by barotrauma. It is also evident that efficient gaseous exchange is dependant on the delivery of appropriate tidal volumes.

Targeted Tidal Volume enables the user to select a target volume that they wish to achieve, allowing the ventilator to adjust PIP and Ti to achieve and maintain the selected tidal volume.

Main benefits of TTV:
- Reduction in volutrauma
- A stable tidal volume accommodating changes in resistance and compliance
- A more stable $PaCO_2$, at the lowest possible pressure resulting in reduced episodes of hypocapnia and hypercapnia
- Reduction in barotrauma
- Ability to self-wean

Pressure Support Ventilation (PSV)

In this mode of ventilation the infant has the ability to trigger and terminate every breath. The main aim of PSV is to reduce the 'work of breathing' (WOB) in the spontaneously breathing infant.

Main benefits of PSV:
- Reduced WOB
- Improved infant / ventilator synchrony
- Reduced need for sedation
- Retraining of respiratory musculature
- Reduced time to wean.

PSV is designed and used in the weaning process and can be used with or without Synchronous Intermittent Mandatory Ventilation (SIMV).

High Frequency Oscillation (HFO)

As claimed by the company, in the SLE 5000, HFO is powerful enough to cater for a wide range of patients from 300 g to 20 kg, dependant on lung mechanics.

The SLE 5000 provides sinusoidal ventilation with *active* expiration.

Main benefits of HFO:
- Improves ventilation at lower pressures
- Higher levels of PEEP can be used without having to use high peak airway pressures to maintain appropriate levels of CO_2

- Produces more uniform lung recruitment
- Reduces airleaks
- Improved oxygenation in infants with severe RDS.
  Without flow termination
  With flow termination.

THE PURITAN BENNETT® 840™ VENTILATOR (FIG. 20.21)

Sensitive, precise breaths to critically ill neonatal through adult patients as claimed by the company.

With highly responsive proportional solenoid valves, an active exhalation valve and state-of-the-art flow sensors, the 840 ventilator provides exceptional responsiveness and control. These features deliver sensitive and precise breaths, and in turn, superior comfort to patients.

Features

SmartAlert™ Alarm System: Prioritized alarm annunciation distinguishes primary alarms from secondary, "dependent" alarms.

- System indicates the urgency level of each alarm to help you efficiently respond to alarm conditions.

Protection from contaminants: A special filter heating process shields patients and clinicians from exposure to viruses and bacteria from exhaled gases.

- Expiratory filter is capable of filtering viruses such as SARS.

Fig. 20.21: The Puritan Bennett® 840 ventilator

Circuit disconnect alarm: Special circuit disconnect alarm does not rely on low pressure or tidal volume to activate.

- When a circuit disconnects, gas flow stops to prevent the spread of contaminants
- Technicians are alerted so they can quickly identify the source of the disconnection.

Self-diagnostic testing: Subsystems are thoroughly checked 100 times per second.

- Message display notifies technicians of potential failures if any drift in performance occurs while ventilating.

The innovative design of the 840 ventilator makes it easy for technicians to set up and navigate. It minimizes training requirements for your staff.

- DualView™ LCD touchscreens display monitored data separately from ventilator settings, so clinicians can change settings and view the impact in one easy place.
- Short self-test feature resets the 840 ventilator settings in between patient use in about two minutes. The test checks for proper ventilation operation and calculates circuit compliance.

AUTHOR'S COMMENTS

A ventilator with pressure control, volume control, wide range of tidal volume from neonate to adult, pressure support, SIMV, Assist control, CPAP, non-invasive ventilation capability (leak compensation), built in high/low pressure alarm, low tidal volume alarm, apnea alarm, power failure alarm with backup battery, low/high oxygen alarm, good humidification and warming system is desirable. Graphics, though optional are becoming a standard feature in most ventilators. SLE and Puritan Bennett ventilators have also become available in India in past few years. Reader is referred to product brochures for details.

Although all these ventilators have mostly proven satisfactory in use, most intensive care units will tend to use one make, so that nursing and medical staff can become familiar with the controls and monitors. Microprocessor technology makes it easy to adapt all these machines to encompass new ventilatory modes, but since there is no clear evidence that any one mode is superior to another it would also seem wise to restrict the problems of patient care and monitoring that are specific to each mode.

Company that provides cost efficient product, hands-on training, good after-sales service and a maintenance contract should be chosen for purchase of a ventilator.

It is also suggested that a user list be requested so the buyer can talk to the users and practical issues and with different ventilators can be discussed with current users.

High cost of ventilators is a big issue (In India , a ventilator may cost anywhere from 7 lakh to 22 lakh Indian rupees (15000 to 50000 US dollars) depending upon the company and product features). With newer Indian companies such as Shreeyash (Pune), ventilator technology is rapidly expanding in this part of the world to make cost effective ventilators (4-6 lakh Indian Rupees) that are clinically tested, and becoming available.

SUGGESTED READINGS

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Appendix 1

Literature Review of Pediatric Ventilation

Praveen Khilnani

ANALYSES OF REFERENCES

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Purpose of Review

Mechanical ventilation is a common intervention provided by pediatric intensivists. This fact notwithstanding, the management of mechanical ventilation in pediatrics is largely guided by a few pediatric trials along with careful interpretation and application of adult data.

Recent Findings

A low tidal volume, pressure limited approach to mechanical ventilation as established by the Acute Respiratory Distress Syndrome Network investigators, has become the prevailing practice in pediatric intensive care. Studies by these investigators suggest that high positive end expiratory pressure and recruitment maneuvers are not uniformly beneficial. High frequency oscillatory ventilation continues to be evaluated in an attempt to provide 'open lung' ventilation. Airway pressure release ventilation is a newer mode of ventilation that may combine the 'open lung' approach with spontaneous breathing. Prone positioning was demonstrated in a recent pediatric trial to have no effect on outcome, while calfactant was found to potentially improve outcomes in pediatric acute respiratory distress syndrome. Ventilator weaning protocols may not be as useful in pediatrics as in adults. Systemic corticosteroids decrease the incidence of post extubation stridor and may reduce reintubation rates.

Summary

Mechanical ventilation with pressure limitation and low tidal volumes has become customary in pediatric intensive care units, and this lung protective approach will continue into the foreseeable future. Further

investigation is warranted regarding use of high frequency oscillatory ventilation, airway pressure release ventilation, and surfactant to assist pediatric intensivists in application of these therapies.

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Objective

To review the various challenges of providing mechanical ventilation to pediatric patients with diseases of increased airway resistance, diseases of abnormal lung compliance or normal lungs.

Sources

Original data from our pediatric intensive care unit and animal research laboratory. Relevant articles included in the MEDLINE electronic database during the last 10 years. Also included were book chapters and definitive studies, as judged by the authors, in the fields of asthma, acute respiratory distress syndrome, mechanical ventilation, ventilator-induced lung injury and permissive hypercapnia.

Summary of the Findings

Mechanical ventilation of patients with diseases of increased airway resistance should center on avoidance of dynamic hyperinflation, allowing complete exhalation prior to the initiation of a subsequent breath and permissive hypercapnia. Positive end-expiratory pressure should be used sparingly to prevent atelectasis and facilitate synchrony in spontaneously breathing patients. Mechanical ventilation of patients with diseases of abnormal lung compliance should take into consideration the inhomogeneous distribution of lung disease. Focus should be on avoidance of volutrauma and atelectrauma that could result in ventilator-associated lung injury.

Conclusion

The last decade was marked by significant advances in the management of pediatric respiratory failure. The choice of mechanical ventilation strategy can significantly influence the subsequent course of lung injury. Mechanical ventilation can no longer be viewed simply as a harmless support modality that is employed to keep patients alive while disease-specific treatments are used to ameliorate the underlying pathology.

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Both invasive and noninvasive mechanical ventilation techniques are inherent to the care of most patients admitted to intensive care units. Despite the everyday use of mechanical ventilation for thousands of patients and the availability of thousands of reports in the medical literature, there are no clear and consistent guidelines for the use of mechanical ventilation for pediatric patients. In many areas data are lacking, and in other areas data are extrapolated from studies performed with adult subjects. Despite the variability in views about mechanical ventilation, 2 themes are consistent. First, modern pediatric respiratory care requires a substantial institutional commitment for state-of-the-art management of the mechanically ventilated patient. Second, a team approach involving physicians, nurses, and respiratory therapists is essential. This review highlights some of the major issues affecting the pediatric patient who requires invasive or noninvasive mechanical ventilation. These issues are pertinent to critical care clinicians because one of the most common reasons for admission to an intensive care unit is the need for mechanical ventilation. Furthermore, the duration of mechanical ventilation is one of the major determinants of the duration and cost of an intensive care unit stay.

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Division of Neonatal-Perinatal Medicine, Department of Pediatrics, F5790, Mott Children's Hospital, University of Michigan Health System, 1500 E Medical Center Drive, Ann Arbor MI 48109-0254, USA. e-mail: *smdonnmd@med.umich.edu*

For more than 40 years conventional mechanical ventilation has been used for the treatment of neonatal respiratory failure. Until relatively recently, this was accomplished with time-cycled pressure-limited ventilation, using intermittent mandatory ventilation. Earlier attempts at volume-targeted ventilation were largely ineffective because of technological limitations. The advent of microprocessor-based devices gives the clinician an option to choose either target variable to treat neonatal patients. This paper reviews the principles of each and the accumulated evidence.

5. Graham AS, Kirby AL. Ventilator management protocols in pediatrics. Respir Care Clin N Am. 2006 Sep;12(3):389-402.

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Management of mechanical ventilation is a complex process with outcomes affected by multiple patient and caregiver variable. Well-constructed protocols represent the synthesis of best available evidence regarding ventilator management. In adults, protocols improve important outcomes such as duration of mechanical ventilation, length of stay, and complication rates; however, protocols are not uniformly successful. In pediatrics, the available evidence does not suggest that ventilator management protocols should be adopted routinely, which may be due to pediatric-specific

attributes such as a generally shorter weaning duration. Evidence suggests support for protocols to carefully titrate sedation. In addition, daily assessment of SBTs improves patient outcomes and should be more uniformly adopted in pediatrics. Ventilator-related outcomes may be affected by other confounding factors such as nutrition and fluid balance. Specific subpopulations, such as children who have congenital heart disease, may present opportunities for focused use of ventilator management protocols. Protocolized ventilation has an important place in trials of new therapeutic strategies such as surfactant or proning. It is hoped that future research will further define the appropriate use of protocols in the general PICU population. Although specific protocols cannot be routinely recommended, a multidisciplinary team approach to synthesizing available literature and determining best practice is a useful model. This approach will foster "team ownership" of ventilator management by all involved, thus engendering the best possible outcomes for critically ill children who require mechanical ventilation.

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Acute lung injury remains a major cause of morbidity and mortality in pediatric intensive care units. Research over the past decade has altered our understanding of the pathophysiology of acute lung injury and the effects of mechanical ventilation on the lung. As a result, approaches to conventional mechanical ventilation of the injured lung are now largely centred around preservation of adequate gas exchange while protecting the lung from further ventilator-induced lung injury. Current techniques for accomplishing these goals include adjusting the ventilator based on the measurement and interpretation of pressure-volume curves, limitation of inspiratory tidal volumes, use of elevated levels of positive end-expiratory pressure, recruiting maneuvers and prone positioning. The currently available data regarding the efficacy and appropriate use of these techniques are reviewed.

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Division of Neonatology, Department of Pediatrics, University of Miami Miller Schoolof Medicine, Miami, FL, USA.

A large proportion of premature infants presents with acute respiratory failure after birth and require mechanical ventilatory support. In addition to conventional mechanical ventilation, an increasing number of these infants are currently supported by newer modes including synchronized, volume targeted and noninvasive mechanical ventilation. While these new modes have improved weaning from mechanical ventilation they have not had a consistent impact on respiratory outcome or other morbidities. This is a review of the different modes of invasive and noninvasive

mechanical ventilation used to support premature infants with respiratory failure.

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Mechanical ventilation is a common form of support in the modern day intensive care unit (ICU). In order for the clinician better to understand and apply mechanical ventilation, it is important that they understand the physiological principles of ventilation. This review describes these basic concepts; parameters of mechanical ventilation, high frequency ventilation and non-invasive ventilation. An overview of ventilatory strategies for four common diseases seen in paediatric and neonatal ICUs will be discussed.

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Appendix 2

Adolescent and Adult Ventilation

Basic Ventilatory Modes

The objectives of positive pressure ventilation are to support and manipulate pulmonary gas exchange, increase lung volume, and decrease the work of breathing and in so doing to unload ventilatory muscles . The main clinical indications for mechanical ventilation are acute respiratory failure, acute exacerbation of chronic obstructive pulmonary disease, coma, and neuromuscular disorders . Acute respiratory failure includes acute respiratory distress syndrome, heart failure, sepsis, pneumonia, trauma, and complications of surgery. Typically the goal is to provide respiratory support while therapy for underlying causes of the acute event are initiated.

Modes

There are three basic ventilator modes that are commonly used:

- Assist Control (AC),
- Synchronized Intermittent Ventilation (SIMV)
- Pressure Support Ventilation (PSV).

A fourth mode, Pressure Control Ventilation (PCV), is used most often in cases of severely decreased lung compliance, such as with the Acute Respiratory Distress Syndrome (ARDS) . Three main factors differentiate these modes from one another: (1) the trigger to initiate a breath, (2) the target for each breath, and (3) the cycle from inspiration to expiration.

A breath can be triggered either by a time-based signal or by an inspiratory effort that is sensed by the machine.

The target can be a preset volume or a preset pressure.

Cycling refers to the stimulus to switch from inspiration to expiration.

In AC and SIMV, the cycle changes when the set tidal volume is reached. PCV relies on the respiratory rate and the preset pressure. PSV cycles when the flow is sensed to have decreased to 20–25% of the peak flow rate (ie, when the ventilator senses that inspiration is nearing completion).

Assist control ventilation requires the physician to set a tidal volume (TV), respiratory rate (RR), flow rate, fraction of inspired oxygen (FiO_2), inspiratory to expiratory ratio (I:E), and positive end expiratory pressure (PEEP). A minimum minute ventilation (MV) is programmed by setting the TV and RR. In this mode, any respiratory effort that is sensed by the ventilator results in the delivery of a full tidal volume breath.

For example, if the TV is programmed at 500 mL, and the RR at 10, the backup MV is 5 L. Each patient-initiated breath that is sensed by the ventilator results in the delivery of the full 500 mL TV regardless of the patient's effort. Thus, if the ventilator senses four patient-initiated breaths, there will be an additional 2 L of MV delivered to the patient making the total MV 7 L.

Advantages of this mode include the ability of the patient to set their own minute ventilation, which can be useful in situations in which there is a large MV requirement. Potential problems with assist control can occur in patients who have a rapid respiratory rate. If the net respiratory rate is such that there is inadequate time for exhalation, the result may be inadequate lung emptying . This can lead to air trapping and a decrease in venous return caused by an increase in intrathoracic pressure programmed at 500 mL, and the RR at 10, the backup MV is 5 L.

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Thus, if the ventilator senses four patient-initiated breaths, there will be an additional 2 L of MV delivered to the patient making the total MV is 7 L. Advantages of this mode include the ability of the patient to set their own minute ventilation, which can be useful in situations in which there is a largeMV requirement. Potential problems with assist control can occur in patients who have a rapid respiratory rate. If the net respiratory rate is such that there is inadequate time for exhalation, the result may be inadequate lung emptying . This can lead to air trapping and a decrease in venous return caused by an increase in intrathoracic pressure.

SIMV is another commonly used mode of ventilation. It also has a backup MV based on the programmed TV and RR. If the patient makes a respiratory effort during a short time period before the delivery of a mandatory breath (known as the synchronization period), the next mandatory breath is delivered at the programmed TV. If the patient initiates a breath outside of this period, the TV completely depends on the patient's spontaneous TV.

Often a level of pressure support is added to this mode. This augmentation of flow is caused by the machine's delivery of the inspired FIO_2 at a preset pressure. Thus, any addition to the preset MV is because of patient effort, augmented only by the pressure support. For example, if the set TV is 500 mL and set RR is 10/min, the programmed MV is 5 L (0.5 L × 10). If the patient initiates four spontaneous breaths with a measured TV of 300 mL, then the spontaneous MV is 1.2 L (0.3 L × 10). The total MV would then be 6.2 L.

Although in AC and SIMV the volume of the breath that is delivered is based on the set TV; in PCV the volume of the delivered breath is based on the level of pressure that is programmed.

Thus, depending on the compliance of the patient's lungs, the pressure threshold is reached at differing tidal volumes . Rather than programming a tidal volume, the physician programs an inspiratory pressure. The other variables that are set include RR, PEEP, FiO_2, and the inspiratory:expiratory (I:E) ratio. The ventilator determines the flow rate. The flow is higher at

the start of inspiration and then decreases as inspiration proceeds to minimize peak airway pressures. This is especially useful in poorly compliant lungs. For example, if the pressure is set at 20 cm H_2O, the RR at 20, with an I:E of 1:1, the observed tidal volume depends on the patient's lung compliance. If the patient has poorly compliant lungs, the TV may be 250 mL. If the patient has better compliance, the TV may be 800 mL. In either situation, the peak airway pressure will not exceed the inspiratory pressure that is programmed. Because the RR often is set higher in patients with poor compliance, it is important to assess for the occurrence of auto-PEEP. Inversion of the I:E ratio can further limit airway pressure in patients with noncompliant lungs. Caution must be exercised when using this mode, however, as it can resultin hypercarbia, which can lead to elevated intracranial pressure, acidosis,and decreased myocardial contractility . Furthermore, decreased expiratory time can result in the stacking of breaths and the consequences of auto-PEEP.

Positive end-expiratory pressure (PEEP) is a level of positive pressure that is maintained within the airways even at the end of expiration in an effort to prevent alveolar collapse and to recruit nonfunctioning lung tissue. Normally during mechanical ventilation the volume of gas that is inspired is exhaled completely. At end-expiration the alveolar pressure is equal to atmospheric pressure. With PEEP, there is a preprogrammed level of positive pressure maintained at the end of exhalation. PEEP is now used regularly in mechanical ventilation. Ashbaugh first noted improvement in oxygenation with increased PEEP . There are several methods by which this effect occurs, including increased functional residual capacity, alveolar recruitment, improved ventilation-perfusion matching, and redistribution of extravascular lung water . The advantages of PEEP are balanced by its potential detrimental effects. A worsening of gas exchange is possible if an increase in dead space ventilation occurs .

Auto-PEEP is a phenomenon that is seen most often in patients with airflow limitation or with high respiratory rates combined with a shortened expiratory time. In this situation, expiration to functional residual capacity is not accomplished before the next inspiratory cycle begins , resulting in dynamic hyperinflation. This means that breathing occurs on a less optimal part of the pressure-volume curve and, thus, there are less efficient respiratory mechanics and an increased work of breathing. Auto-PEEP can cause an inability of the ventilator to sense a respiratory effort on the part of the patient because of an inability to reach a negative flow. Thus, the patient's efforts are not aided by pressure support or by a mechanical breath, further leading to increased patient effort. It is therefore important to recognize that improved oxygenation does not always occur with PEEP and vigilance is necessary to avoid complications. Correctly determining the level of PEEP that is most effective for a patient depends on the nature of the lung disease being treated. Recruitment of atelectatic areas is balanced by overdistention of normally aerated areas and must be individualized to prevent barotrauma.

Pressure support (PS) helps increase a patient's own inspiratory effort by providing an augmentation of flow during a patient-initiated breath.

In essence this helps to decrease the negative pressure necessary for a patient to initiate a breath of sufficient tidal volume. Airway resistance is considerable when breathing through an endotracheal tube, especially when connected to the circuit of a ventilator. PS therefore, can be used to decrease the effort required to maintain adequate spontaneous respiration. The inspiratory assistance of PS ceases when the flow rate decreases to 20–25% of the peak flow rate. This decrease in flow rate signals the beginning of passive exhalation. PS can be used with SIMV to help assist the patient during their spontaneous breaths without providing a full tidal volume breath, as would be the case in assist control mode. SIMV with pressure support has been found in some studies to be more comfortable and more efficient in respiratory muscle workload than other modes of ventilation. PSV also can be used as an independent mode in patients with adequate respiratory drive and strength and often is used in conjunction with a level of PEEP. Some studies have found this mode to be more efficient than AC ventilation in patients who have adequate respiratory drive and strength to meet their minute ventilatory demands. The best mode for a given patient depends on the indications for mechanical ventilation and the characteristics of the patient. For instance, in a patient whose minute ventilation requirements are large but who is unable to draw sufficient tidal volumes, assist control may be the optimal mode because any sensed breath results in the delivery of a full tidal volume. The potential exists, however, for hyperventilation and respiratory alkalosis and for auto-PEEP if there is incomplete exhalation between breaths. Likewise, the patient with high airway pressures may require pressure support ventilation to minimize the risk for barotrauma. In general, however, SIMV is the mode most appropriate for initiating ventilation for most patients. One study found SIMV with pressure support to be the most efficient mode in the required work of breathing. There are many alternative modes of ventilation that are emerging, most of which are undergoing clinical evaluation, although some have been in existence for some time. There are several high frequency modes of ventilation including high-frequency positive pressure ventilation, highfrequency jet ventilation (HFJV), and high-frequency oscillation. HFJV is used most often during rigid bronchoscopy in the operating room but also is used in patients with poor lung compliance. Other modes available include airway pressure-release ventilation, proportional-assist ventilation, and servo-controlled pressure support. Detailed discussion of these modes is beyond the scope of this article but some may prove to be of use in the future.

Ventilator Settings

The initial settings that are necessary vary depending on the chosen mode.

FiO_2

Often the initial settings start with a high FiO_2 to assure adequate oxygenation during the initial stabilization of the patient and while other ventilator settings are being optimized. The FiO_2 typically is then titrated

to maintain an oxygen saturation of 90%. In certain situations in which pulmonary dynamics limit oxygenation, such as severe ARDS, lower oxygen saturations may be acceptable.

Tidal Volume

This is programmed in AC and SIMV modes. It is usually recommended that TV is set between 5–8 mL/kg. In patients with normal lungs, tidal volumes of up to 10 mL/kg may be used, whereas lower volumes are required in patients with decreased compliance.

Respiratory Rate

There can be wide variations in the RR, which is programmed. The rate often depends on a given patient's physiology and the goals for minute ventilation. The range is usually between 6 and 30 breaths/min. The higher RR often is used in ARDS with a low tidal volume to maintain minute ventilation or in cases in which it may be desirable to hyperventilate a patient to decrease the PCO_2.

Inspiratory Pressure

This is set in pressure control ventilation. The goal is to maintain plateau pressures less than 35 cm H_2O to minimize the risk for barotrauma. Commonly used initial settings are in the range of 10–30 cm H_2O.

Pressure Support

This is set in PS ventilation and in the SIMV mode when PS is used. The usual range for PS is 5–30 cm H_2O. Higher levels result in greater augmentation of the patient's own respiratory effort.

Trigger Sensitivity

This is the amount of negative pressure that the patient must establish for the machine to sense patient effort. Appropriate adjustment of the trigger sensitivity is essential to allow the ventilator to deliver a breath that is synchronized with the patient's own respiratory effort while ensuring that it does not cycle too often. This is usually set at 1 to 2 cm H_2O. Flow triggering is an alternative to pressure triggering, wherein the initiation of a patient's respiratory effort is sensed as a decrease in flow rate as opposed to a decrease in pressure. This is usually set to trigger when the baseline flow decreases by 1–3 L/min. Flow triggering may decrease the work of breathing, especially in patients in danger of developing auto-PEEP.

Positive end Expiratory Pressure

PEEP is the level of positive pressure that is maintained in the airways at the end of expiration. It typically ranges from 5–20 mm H_2O, depending on the underlying lung pathology.

Inspiratory: Expiratory Ratio

This ratio determines the amount of time in a ventilatory cycle that is spent in inspiration versus that which is spent in exhalation. I:E often is set initially at 1:2. In some situations it can be changed to 1:1 or even to an inverse ratio such that the expiratory time is shorter than the inspiratory time in an effort to recruit collapsed alveoli and increase mean airway pressure to improve oxygenation. In obstructive lung disease, the I:E may need to be increased to greater than 1:2 to permit complete emptying of the inspired volume.

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