Part II: Respiratory Failure

Chapter 22: Mechanical Ventilatory Support

T E Oh

Respiratory support forms a major part of an Intensive Care workload, and is rarely required in isolation from other problems which may have their own adverse effects on respiratory function. There is a wide diversity of conditions leading to acute respiratory failure requiring mechanical ventilatory support. Some patients with acute lung disease can, however, be successfully treated without tracheal intubation and mechanical ventilatory support, using continuous positive airway pressure (CPAP) via a tight fitting anaesthetic face mask. Other accepted terms for mechanical ventilation include artificial, controlled, assisted, and intermittent positive pressure ventilation (IPPV), and continuous mechanical ventilation (CMV).

Indications

The classic indication for ventilatory support is reversible acute respiratory failure. Guidelines for instituting ventilation may be based on respiratory mechanics, oxygenation, and ventilation (Table 1). However, it is the trend of the values together with the clinical situation, which decides the need for intervention. Each respiratory variable must always be evaluated in the clinical context. If the clinical condition of the patient demands urgent ventilation, then complete assessment of the respiratory variables is unwarranted.

Ventilatory support is also indicated in certain serious disease states for the maintenance of adequate oxygenation and carbon dioxide elimination (Table 2).

Physiology of Mechanical Ventilation

Cardiovascular Changes

Mechanical ventilation is achieved by applying IPPV through an endotracheal tube. Compared with spontaneous ventilation, there is a reversal of pressure gradients with large pressures being applied. There is an increase in the mean intrathoracic pressure, with a resultant reduced venous return and fall in cardiac output. Left ventricular output is also decreased from a fall in right ventricular ouput, secondary to increased right ventricular afterload (due to pulmonary microvascular compression during inspiration). If normal vascular reflexes are preserved, peripheral venous tone increases, restoring the venous gradient for return to the heart. This compensation fails when hypovolaemia exists, or when sympathetic responses are impaired.

The reduction in pulmonary blood flow leads to an increase in pulmonary vascular resistance which may be of importance when ventilating patients with lung disease. Adverse haemodynamic effects of IPPV may be minimized by maintaining an inspiratory:expiratory time ratio of less than 1, and by using rapid rates of inflation.

A less appreciated and unexpected effect of IPPV is an *increase* in left ventricular stroke volume during early inspiration. This is due in part to left ventricular compression by the raised intrathoracic pressure, and possibly also to reduced afterload from an increased pressure gradient between intra- and extrathoracic vascular beds. Thus cardiac performance in patients with severe left ventricular function may be improved by CMV, but this awaits further evaluation.

Lung Changes

IPPV results in some unfavourable pulmonary physiological effects, ie, maldistribution of gas, progressive atelectasis with a reduced functional residual capacity (FRC), increased ventilation:perfusion (V/Q) mismatch, decreased compliance, and a reduction in surfactant. In spontaneous breathing, both ventilation and perfusion is preferentially distributed to the dependent zones of the lungs. With IPPV, however, preferential ventilation of the non-dependent regions occurs, resulting in increased (V/Q) mismatch. IPPV in the supine position also leads to decreased FRC, due in part to decreased lung volume from cephalad displacement by the diaphragm and abdominal contents. The loss of lung volume contributes to microatelectasis and decreased compliance. Decreased pulmonary hypoperfusion from IPPV, especially in the non-dependent regions, with maldistribution of gas, lead to increased alveolar dead space (increased dead space:tidal volume (V_D:V_T) ratio). Dead space ventilation increases with rapid rates, age, and lung pathology.

Venous admixture increases with IPPV because of multiple variables, ie, increased V/Q mismatch, decreased FRC and progressive atelectasis. Periodic hyperinflation or "sighs" have been used to counteract atelectasis. However, the evidence for progressive atelectasis during IPPV is conflicting, and "sighing" is not now though to be important. Progressive atelectasis is less of a problem with larger tidal volumes, and surfactant recution may occur only with gross overdistention of alveoli. Venous admixture and the alveolar-arterial gradient (PAO_2-PaO_2 or A-aDO_2) has been shown to be reduced by using larger tidal volumes (ie, 12 mL/kg), or by the addition of positive end expiratory pressure (PEEP).

Respiratory Alkalosis

Over-ventilation may produce moderate hypocarbia. Respiratory alkalosis decreases cardiac output, causes cerebral vasoconstriction, and increases haemoglobin affinity for oxygen (by causing a leftward shift of the oxygen dissociation curve). In addition, weaning from the ventilator may prove more difficult. Hypocarbia can corrected by the use of mechanical dead space.

Other Changes

Mechanical ventilation reduces the oxygen consumption required for respiratory work, which may vary from 2-3% at rest up to 40-50% in severe respiratory distress.

Antidiuretic hormone secretion is increased leading to water retention, and this is often accompanied by sodium retention as a result of the illness or surgery. Aldosterone secretion has also been reported to be increased by PEEP.

Assisted Ventilation

"Triggering" (or assist mode in North American terminology) is a system whereby the ventilator begins inspiration only after a spontaneous breath by the patient reduces airway pressure and initiates the ventilator cycle. The tidal volume is set by the intensivist and the patient determines the rate. For safety reasons, ventilators offer only an assist/control mode whereby the ventilator will deliver predetermined breaths if there is no spontaneous breathing by the patient. The theoretical advantage of "triggering" is to reduce inspiratory pressure and co-ordinate patient and ventilator. In practice, hyperventilation and patient exhaustion are commonly seen, and "triggering" is of little use other than to implement weaning or recovery from respiratory failure secondary to central depression.

Pressure support (assist) ventilation is a different entity to the above North American term for triggering. It is a technique which provides a constant preset airway pressure at the start of inspiration. Pressure support levels of 5-15 cm water (0.5-1.5 kPa) are usually used, which ceases after a given fraction of inspiratory time, or when inspiratory flow falls below a predetermined fraction of the initial inspiratory flow rate. Expiration is passive. The pressure support level is gradually decreased as the patient improves. Although there has been isolated case reports, consistent, clear clinical advantages over intermittent mandatory ventilation (below) or vice versa, have not been proven.

Intermittent Mandatory Ventilation

Intermittent mandatory ventilation (IMV) systems allow spontaneous breathing between the "mandatory" ventilator delivered breaths. The mandatory ventilation is further reduced by a reduction in ventilator frequency as the patient's ability to increase his own spontaneous minute volume improves. The spontaneous tidal volume is directly related to the patient's effort, whereas with "triggering", it remains a function of the ventilator. By allowing for some spontaneous breathing, IMV offers the following advantages:

1. There is a reduced need for sedation and muscle relaxants can be avoided.
2. A slower ventilator rate is possible thus allowing for potentially less barotrauma.
3. Venous return via the thoracic pump mechanism is augmented (by spontaneous breathing). Cardiac output is less depressed and higher levels of PEEP may be used when necessary.
4. The weaning process is facilitated, in part by the graduated exercising of respiratory muscles.

Synchronized IMV (SIMV) is a modification whereby the mechanical breaths are provided by triggered ventilation. If no breath is triggered within a predetermined time period, a mandatory ventilator breath is automatically delivered. There does not appear to be any clear cut clinical advantages of SIMV over IMV in critically ill patients.

Although IMV was originally introduced as a method to wean patients off controlled ventilation, it is now commonly used as an alternative to CMV. IMV may be instituted at the start, or after a 24-48 hour "rest period" of CMV. An initial minute volume of approximately 100 mL/kg with a rate of 8-10/min can be set, and the settings can be adjusted according to arterial blood gas measurements.

Mandatory Minute Volume

Mandatory minute volume ventilation (MMV) is another relatively new mode of mechanical ventilatory support. Essentially, the MMV system ensures that the patient always receives the same preset total (spontaneous and ventilator) minute volume. The spontaneous volume is measured by the ventilator which then contributes the remainder of the preset minute volume. In the early stages of ventilation, the patient's breathing is supported considerably by the ventilator. As the patient improves, his own spontaneous efforts contribute more to the minute volume, and ventilation by the machine automatically, gradually decreases. In contrast to IMV, progressive manual adjustments to the ventilator are unnecessary, ie, the patient "self-weans". However, MMV circuits are relatively complicated. Spontaneous shallow, ineffective tidal volumes may not be differentiated by the ventilator, which would only sense the total spontaneous minute volume and thus inappropriately, contribute an inadequate mandatory volume. Its exact role in controlled ventilation still requires further evaluation.

Optimal Ventilatory Pattern

To offset the adverse haemodynamic and lung changes with IPPV and optimal ventilatory pattern can be:

1. A large tidal volume (10-15 mL/kg body weight) to minimize the increase in venous admixture (although dead space may increase in diseased lungs due to overinflation of more normal regions). Patients also tolerate large tidal volumes better than normal volumes of 7 mL/kg.

2. A relatively slow rate (10-12/min) to prevent large rises in V_D:V_T ratio.

3. An inspiratory:expiratory time (I:E) ratio of less than 1. Patients with obstructive airways, ie, chronic obstructive airways disease or asthma may need smaller ratios, ie, 1:3.

A *decelerating inspiratory waveform* has been suggested to lower airway resistance and improve gas distribution and oxygenation. *Accelerating flow* increases mean airway pressure and dead space. Nonetheless, clinical investigations on inspiratory waveforms are inconclusive, and waveform is not considered important provided the I:E ratio is kept below 1:1.

Inverse (or reverse) ratio ventilation uses a longer inspiratory (than expiratory) time. Advantages claimed are improvement in oxygenation and CO_2 elimination, from an effect of increasing FRC similar to that of PEEP. Disadvantages are also those seen with PEEP. This technique was first reported in children, but has since also been used in adults. I:E ratios of between 1.1:1 and 1.7:1 are deemed optional for oxygen delivery. Inverse ratio ventilation is commonly used with low levels of PEEP/CPAP, inspiratory hold, and low ventilation rates.

A *negative phase in expiration* (or *negative end expiratory pressure*) may help venous return to the heart but should preferably not be used. Most ventilated patients compensate adequately and volume deficit correction and/or inotropic agents are more important. Moreover, a negative expiratory phase may worsen ventilation: perfusion mismatch by encouraging airway closure at lung volumes near to FRC. *Expiratory flow retard* has been used to avoid premature airway collapse and air trapping in obstructive airways disease, but clinical usefulness is unproven.

As IPPV has physiological disadvantages, there has been increased use of ventilatory modes with a spontaneous breathing component (IMV or pressure support) or CPAP as alternatives to CMV, rather than as weaning techniques. Nevertheless, in the dangerously hypoxic patient, IPPV remains the mainstay management.

PEEP

More favourable distribution of inspired gas occurs with the use of PEEP. In general, PEEP is indicated when an adequate fractional inspired oxygen concentration (FIO_2) fails to maintain satisfactory oxygenation (ie, PaO_2 60 mmHg or 8 kPa or less). PEEP is used by some "prophylactically" during controlled ventilation (as it will nearly always improve oxygenation), but there is no evidence that "prophylactic" PEEP alters the course of the acute lung disease. PEEP improves oxygenation probably by reducing terminal airway closure and increasing FRC leading to a reduction in $A\text{-}aDO_2$.

The usual range employed is 5-15 cm of water (0.5-1.5 kPa) but higher values have been used. With the use of higher pressures, the fall in cardiac output caused by the raised intrathoracic pressure may counteract the beneficial effects of PEEP on oxygenation. Optimal levels of PEEP can be found with the use of pulmonary capillary wedge pressure (PCWP), cardiac output, and mixed venous oxygenation tension measurements, and with appropriate use of inotropic agents. However, PCWP readings in the presence of PEEP need to be interpreted with caution. When CVP and PCWP measurements are not available, lung compliance and the clinical indices of cardiac output may be used to derive an optimal PEEP level. PEEP may be applied with IMV to lessen the decrease in cardiac output. Higher levels of PEEP may then be introduced but the increased attendant risk of barotrauma.

In a few patients PEEP may worsen PaO_2, though to be due to extensive redistribution of pulmonary blood flow to non-ventilated regions of the lung, thus increasing the shunt fraction. Other adverse effects of PEEP include reduced renal blood flow, raised intracranial pressure, and an increased risk of barotrauma. PEEP is further discussed in Chapter 25, Acute Respiratory Distress Syndrome.

CPAP

Since PEEP is a residual airway pressure above atmospheric at the end of expiration, it can be used during spontaneous or mechanical ventilation. With spontaneous PEEP (SPEEP), the airway pressure becomes less positive during inspiration, and eventually negative at the height of inspiration. CPAP may also be used during spontaneous ventilation. It is *continuous* positive airway pressure, with positive airway pressure maintained *throughout* the whole respiratory cycle. CPAP need not be confined to spontaneous breathing. It may be used with IMV, becoming effective during the spontaneous breathing phase.

The physiologic lung effects and disadvantages of CPAP are similar to PEEP, CPAP or SPEEP is provided by differences in circuit design. Attention to circuit resistances and expiratory valves of ventilators are extremely important, as work of breathing may be markedly increased. Work of breathing is least when positive airway pressure is constant, ie, less with CPAP than SPEEP.

CPEEP/SPEEP may be applied via a face mask, endotracheal or tracheostomy tube, and specially designed nasal prongs or nasal mask. Tight-fitting face mask CPAP/SPEEP offer an alternative to intubation in certain selected patients in respiratory failure, but facial skin pressure lesions and aspiration risks are disadvantage. The risk of aspiration may be reduced with concomitant use of a nasogastric tube to prevent gastric distension. Nasal devices are better tolerated and safer than face masks, but mout breathing tolerated and safer than face masks, but mouth breathing reduces effectiveness. They are used in children and for managing obstructive sleep apnoea. In general, CPAP/SPEEP may be used in spontaneously breathing patients in acute respiratory failure, and during weaning.

Management of Mechanical Ventilatory Support

Nursing Care and Observations

Nursing care is vitally important in patients receiving mechanical ventilatory support. When ventilation is controlled completely with sedation and paralysis, the nursing care will be the same as that of an unconscious patient. Additional observations, however, need to be made and recorded. The patient's colour, chest movements, air entry to both sides, and synchronization with the ventilator should be observed frequently between regular recordings of vital signs. Recordings of inflation pressure, frequency, expired minute volume or tidal volume, FIO_2, and inspired gas temperature should be carried out every hour. Tube intracuff pressure should be checked every time the cuff is inflated. Circuit leaks must be detected and the ventilator alarm systems should not be switched off. Patient communication is important. A ventilated patient must always be spoken to as if he were fully awake and alert. A brief explanation should be given prior to any procedure being performed.

Patients on life-support such as a ventilator should never be left unattended, because failure of the system or development of life-threatening complications (ie, pneumothorax) may occur. Hence the nurse must be alert to any sudden changes in system performance, or any acute development of patient distress, cyanosis, tachycardia, increased inflation pressure, and unequal air entry.

Clearance of Secretions

Endotracheal suction is a very important aspect of the care of intubated patients. It should be performed with a sterile glove technique. The catheter is introduced gently into the trachea, and intermittent suction is applied as the catheter is slowly rotated and with drawn. This procedure should be limited to 15 seconds. Manual hyperinflation of the lungs with 100% oxygen should be done for 2-3 minutes before and after suction. The use of PEEP in this pre-oxygenation inflations may improve oxygenation and minimize suction desaturation in hypoxic patients with decreased FRC. If PEEP or CPAP is already being applied, a self-sealing endotracheal tube adaptor should be used with tracheal suctionings. Severe oxygen desaturation may otherwise occur on disconnection from the ventilator (when positive airway pressure is lost). Vibration or percussion of the chest during lung deflation from a hyperinflated position helps to loosen secretions so that they may be removed by suction. Aspirated sputum should be sent for microbiologic culture and sensitivity tests.

Sedation

Sedative and muscle relaxant drugs are given to the patient to enable synchronization with the ventilator. "Fighting" the ventilator leads to uncoordinated ventilation, increased oxygen consumption, and increased risk of complications from the endotracheal tube (ie, accidental extubation, and laryngeal damage). The drugs used include midazolam, opioids, alcuronium, and pancuronium. Requirements vary from patient to patient, but inadequate sedatio or oversedation are to be avoided. A continuous infusion of a sedative is preferable to intermittent IV injections. Requirements for sedation are lessened with the use of spontaneous breathing modes.

Monitoring of Ventilatory Therapy

1. *Arterial Blood Gas*

Serial arterial blood gas (ABG) estimations are the most direct and accurate means of assessing adequate oxygenation and carbon dioxide elimination. Any adjustment or change of ventilatory parameter (ie, FIO_2, minute volume, or mechanical dead space) should be assessed 20-30 minutes later by an ABG analysis. The effect of altering PEEP on gas exchange could be assessed earlier, as FRC and PaO_2 changes probably occur within one to two minutes after a change in PEEP. Although nomograms are available for the required dead space to achieve normocarbia they are unreliable in clinical practice. Dead space increments of 50-100 mL should be checked by ABG analysis so that the desired $PaCO_2$ level can be attained.

2. *Pulse Oximetry*

Continuous oxygen saturation monitoring by non-invasive pulse oximeters are recommended for severely hypoxic and haemodynamically unstable patients. Adjustments or changes of ventilatory parameters and modes can be made with oxygenation responses observed almost immediately. Pulse oximetry is more practical and commonly used than invasive continuous mixed venous oxygen saturation.

3. *End-Tidal* CO_2

Continuous monitoring of end-tidal expired CO_2 using a CO_2 analyzer is useful in certain situations, ie, therapeutic hyperventilation, but is not routinely necessary.

4. *Lung Function Tests*

Assessment of ventilation: perfusion mismatch can be performed regularly by measuring $A\text{-}aDO_2$ and the $V_D{:}V_T$ ratio. Tests of ventilatory capacity may be indicated in some patients, but tests of lung mechanics are generally not practical.

5. *Serial Chest X-Rays*

Weaning

An aim of ventilatory therapy is to wean off mechanical ventilatory support as soon as practicable. On the other hand, weaning should not be attempted before the patient has recovered sufficiently to regain adequate ventilatory and pulmonary reserves. Guidelines for weaning are essentially the converse of values used for instituting controlled ventilation. In general, weaning will not be successful if there is an accompanying major organ failure, or if the patient still requires a high FIO_2 to maintain adequate oxygenation. Nevertheless, the decision to initiate the weaning process is often subjective as traditional criteria can be unreliable. Weaning can be initiated without having to discontinue PEEP first, as was previously recommended.

Weaning is traditionally accomplished with a T-piece system, using adequate humidification and oxygen concentration. The use of PEEP can be replaced with CPAP using the appropriate CPAP valve and circuit. There must be no residual effects of sedatives or muscle relaxants. Vital signs, ABGs and respiratory variables should be monitored closely during the weaning process. The CPAP is gradually decreased in line with satisfactory PaO_2 results. Periods of spontaneous ventilation are gradually lengthened until mechanical ventilatory support is required only at night. The patient is then taken off the ventilator at night after at least 2 consecutive days of spontaneous breathing. Removal of the tracheostomy tube may be carried out after another 2-3 days. If secretions are troublesome, replacement with a smaller tube or a fenestrated tube enables removal of secretions and allows the patient to breath more easily.

The use of IMV and/or pressure support in weaning avoids the drastic change from CMV to spontaneous breathing via a T-piece. Ventilator delivered breathing is progressively reduced as the patient's respiratory function improves. The patient is then weaned to spontaneous breathing by a T-piece or CPAP when IMV ventilator breaths are as low as 3-4/min or pressure support required is less than 3 cm water (0.3 kPa). IMV and/or pressure support may be useful in patients who are difficult to wean off CMV (ie, chronic bronchitis and those with prolonged ventilatory support). Weaning time may be shortened in these patients.

Other Methods of Ventilation and Gas Exchange

High Frequency Ventilation

"High frequency ventilation" is a confusing term which does not refer to a single homogenous entity. Three main basic techniques can be identified.

1. *High Frequency Positive Pressure Ventilation (HFPPV)*

HFPPV delivers humidified gas through an insufflation catheter, bronchoscope, or cuffed endotracheal tube, at a preferred rate of 1-2 Hz (60-120/min). Adequate alveolar ventilation and arterial oxygen can be achieved with a reduction of peak airway pressure (and circulatory interference), and an improvement in pulmonary gas distribution. It has been successfully used during laryngoscopy and bronchoscopy, and in adult and neonatal intensive care. The performance of HFPPV may be specific to the device, as reported features refer to a device of small internal volume and static compliance.

2. *High Frequency Jet Ventilation (HFJV)*

This is probably the most widely used form of HFV used today. HFJV delivers dry gas under a high pressure (about 50/lbsq inch or 345 kPa) at rates of 2-10 Hz (120-600/min), by means of fluidic solenoid, or rotating valve flow controllers. Driving pressure, frequency and I:E ratio are usually adjustable. Gas entrainment in the proximal airway is common but not invariable. Expiration is passive and PEEP may be added. Humidification depends on entrainment of additional humidified gas through a side arm, placing a humidifier before or after the cycling device, or a saline drip into the circuit, immediately in front of the jet nozzle. The optimal positioning of the jet nozzle within the trachea is unknown. Gas exchange occurs by ordinary convective gas transport, possibly enhanced by some turubulent mixing generated by the jet, as tidal volumes are extremely small at 1.0-2.5 mL/kg. Although peak airway pressure is reduced, barotrauma has occurred, since exhalation is dependent on passive lung and chest wall recoil driving gas out of the endotracheal tube. HFJV has been successfully used to treat bronchopleural or tracheal disruption, bronchopleural fistula, ventilator weaning and emergency percutaneous trans-tracheal ventilation. It has been associated in neonates with tracheal injury and obstruction due to inadequate humidification.

3. *High Frequency Oscillation (HFO)*

HFO used a piston, loudspeaker or similar device to oscillate at 3-20 Hz (180-1200/min), and drive a very small volume of gas into the airway and suck an equal volume back out. A steady fresh gas (bias) flow at the top of the endotracheal tube provides oxygen and removes carbon dioxide. Alveolar gas exchange is postulated to be due to facilitated diffusion. A higher mean airway pressure can be achieved, but less than peak airway pressure by conventional means. Ventilation-perfusion inequalities may be minimized. HFO currently remains more of a research rather than clinical technique.

4. *Combined High Frequency Ventilation (CHFV)*

A combination of CMV (usually at slower rates) with a HFV technique, either between or superimposed upon CMV breaths is possible. There have been isolated reports of CHFV, but this hybrid mode has yet to be clinically evaluated in full.

The role of high frequency techniques in Intensive Care awaits further evaluation. Many issues such as humidification, optimal characteristics and technical device flaws still remain unresolved. Variations of a technique may be adapted to different clinical situations. However, high frequency ventilation has not been shown to offer major advantages over conventional modes of ventilation.

Independent Lung Ventilation

Independent lung ventilation (ILV) is achieved by using a double lumen endobronchial tube to ventilate each lung separately. Plastic double lumen tube ("Broncho-cath", National Catheter Co) are preferred to more irritant traditional rubber Carlens or Robert-Shaw tubes.

Two ventilators are usually required and settings and ventilatory modes can be selectively applied without need for synchronization. ILV is an acceptable form of ventilatory support in respiratory failure with a unilateral or different lung pathology such as unilateral oedema, aspiration, or chest trauma.

Extracorporeal Membrane Oxygenation (ECMO)

Controlled trials have shown no benefits of ECMO over conventional ventilation. A modified technique of extracorporeal CO_2 removal with low frequency IPPV and PEEP has been reported to produce good results in critically ill severely hypoxic patients. Cost, logistical and technical difficulties limit use of EMO in Intensive Care.