Principles of artificial ventilation

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Abstract

The application of intermittent positive pressure ventilation (IPPV) during the 1952 Copenhagen polio epidemic led to the development of the world's first intensive care unit. The requirement for ventilatory support is the most common indication for intensive therapy unit (ITU) admission and is a defining feature of the specialty. Ventilator technology continues to develop and there are many ways to deliver IPPV. The variety of modes of ventilation is increasingly complex and expanding, without evidence that any one mode is associated with improved outcome. Ventilatory support is part of the treatment for a range of conditions including acute respiratory failure, raised intracranial pressure (ICP) and circulatory shock. Ventilator-associated lung injury is reduced by using low tidal volumes and limiting plateau airway pressure to less than 30 cmH_2O. Prolonged artificial ventilation has an associated morbidity and mortality and thus should be reviewed by an expert clinician on a daily basis. Weaning aims to identify those patients who will be able to breathe spontaneously. Protocols exist to facilitate timely extubation without the need for re-intubation.

Keywords Artificial ventilation; lung-protective ventilation; weaning

Royal College of Anaesthetists CPD Matrix: 2C02

Learning objectives

After reading this article, you should be able to:

- describe how to initiate, manage and wean artificial ventilation
- list different modes of ventilation and the rationale for their use
- manage artificial ventilation in patients with asthma, COPD (chronic obstructive pulmonary disease) and ARDS (acute respiratory distress syndrome)

History

During the early 20th century, mechanical ventilation of the lung was achieved by the application of negative pressure around the body leaving the head free ('iron lung') or around the thorax alone (cuirass ventilators). In 1952, a polio epidemic in Copenhagen resulted in hundreds of patients requiring long-term ventilation due to respiratory and bulbar failure. This overwhelmed the system (they had seven old-fashioned ventilators at the time) until Professor Larssen, the Chief Physician, appealed to Dr Bjorn Ibsen, an anaesthetist, with the idea that intermittent positive pressure ventilation (IPPV), as used in anaesthesia, may rescue the situation. Over 300 patients were manually ventilated around the clock (via tracheostomy) by 1000 medical and dental students. Dr Ibsen cared for these patients on the same ward, and thus can be considered the 'father' of intensive care medicine.

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The first positive pressure ventilators were adaptations of respirators developed during World War II to oxygenate pilots at altitude. Forrest Bird, a WW2 pilot, developed the first 'Bird' ventilators using household materials. The main difference between the two methods of ventilation is that 'iron lungs' decrease intrathoracic pressure to sub-atmospheric, *sucking* air in, whereas IPPV via an endotracheal tube (ETT) increases alveolar pressure above atmospheric, *blowing* air in. This simple difference explains many of the physiological effects associated with IPPV.

Basic classification of ventilators

The variety and complexity of ventilators and modes of ventilation continues to increase, but the basic principles of operation are still best understood by considering each phase of the ventilatory cycle – inspiration, change from inspiration to expiration, expiration, and change from expiration to inspiration.

Inspiration

At any one instant during inspiration, a ventilator may deliver a fixed pressure (pressure generator) or a fixed flow (flow generator). To determine flow rate, practitioners will often select a target volume and an inspiratory time (t_{insp}). Modern ventilators respond to feedback from within the circuit, and can therefore combine elements of flow and pressure generators simultaneously. For example, in pressure regulated volume control (PRVC), the ventilator will deliver the required flow with the minimum possible plateau pressure (P_{plat}).

Pressure generator: the ventilator produces inspiration by delivering a constant, pre-set pressure to the airway. Gas flows at a rate determined by airway resistance, and flow continues to a volume determined by lung compliance. If airway resistance increases, flow rate will decrease; if compliance increases, tidal volume (V_T) will increase. Thus performance varies depending on the patient's physiology.

Flow/volume generator: flow generators deliver a pre-set constant rate of flow to produce inspiration. Over a given inspiratory time this leads to a fixed inspiratory volume. The ventilator is driven by gas at approximately 400 kPa (with a high internal resistance) and therefore it can vary pressure delivered to compensate for changes in compliance and resistance. If compliance decreases (stiffer lungs) the rate of increase of alveolar pressure will be greater for the same rate of distension of the lungs, and the ventilator will compensate by delivering a higher

pressure to the airway (therefore delivering a constant V_T). If airway resistance (a dynamic measure) increases, without a change in compliance, the pressure gradient between tracheal tube and alveoli will increase, but at a given flow rate the alveolar pressure will be the same. The ventilator will deliver higher pressure to the airway to maintain a constant flow rate in the face of increased resistance.

In essence: in a pressure generator, pressure is fixed and flow rate and V_T are the dependent variables. In a flow generator, flow rate, and therefore V_T, are fixed and airway pressure is the dependent variable (Figure 1).

Change from inspiration to expiration (cycling)

Volume-cycling: the ventilator cycles into expiration once a set V_T has been achieved. The inspiratory time is determined by the inspiratory flow rate.

Pressure-cycling: the ventilator cycles into expiration when a set airway pressure has been achieved. This mode will compensate for small air leaks, but V_T will depend on compliance and resistance as will inspiratory time. A modern ventilator may also compensate for small leaks in volume-control mode, by measuring expired volume (V_E) and making appropriate adjustments.

Time-cycling: the most common method in modern ventilators. The duration of the inspiratory phase is pre-determined and with a flow generator, a tidal volume is usually programmed. When this has been delivered, there may be an inspiratory pause while gas re-distributes within the lung (aiding gas-exchange, a phenomenon known as pendelluft) before the inspiratory cycle ends. This preset-volume setting is not the same as volume-cycling, where expiration will automatically begin once the target volume has been achieved.

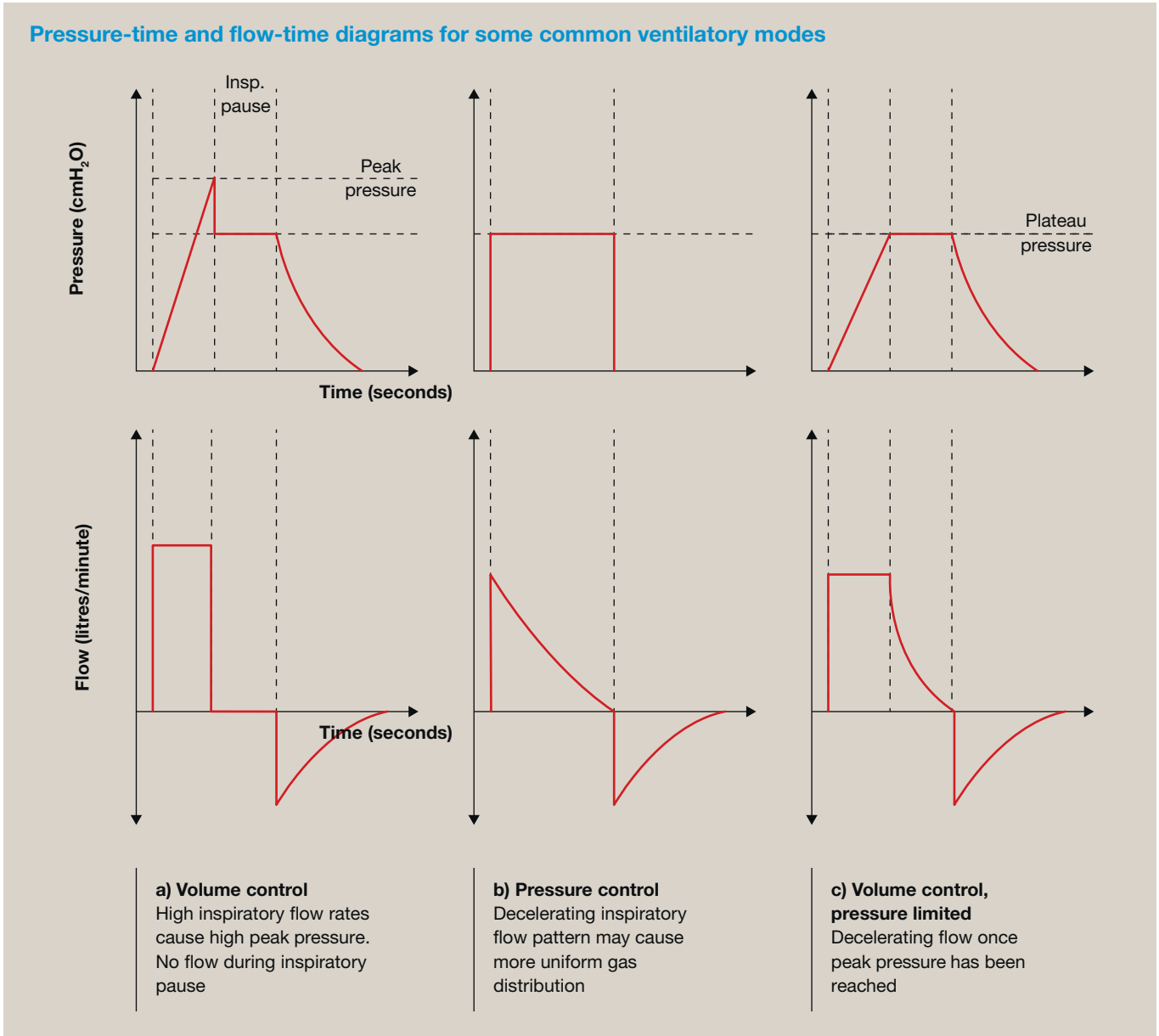

Figure 1

Flow-cycling: in pressure-support ventilation (PS), inspiration will terminate once flow has declined to a pre-determined percentage of maximum flow.

Expiration

There is no active expiration from the ventilator, as the use of sub-atmospheric pressure ('sucking' air out of the lungs) leads to closure of the small airways, atelectasis and gas trapping. Rather, the patient is allowed to passively exhale and flow rate will decrease exponentially. The patient exhales either to atmospheric pressure, or against a set positive end expiratory pressure (PEEP). An exception to this rule is the Ventrain ventilator, in which a narrow lumen tube is used to insufflate and actively remove gas from the lungs. This is a modern invention which is intended for 'can't intubate can't ventilate' (CICV) scenarios when ventilation is achieved via cricothyroidotomy.

Change from expiration to inspiration (triggering)

The ventilator may deliver the next breath based on time criteria, or by pressure or flow changes with the last allowing synchronization with the patient's own respiratory efforts.

Time triggering: inspiration will begin at a time determined by respiratory rate (e.g. every 3 seconds after the last inspiration if the rate is set at 20 per minute) or by the ratio of inspiration to expiration (I:E ratio).

Pressure triggering: the ventilator delivers a breath when the airway pressure decreases to a pre-set level indicating patient inspiratory effort.

Flow triggering: 'flow by' ventilators deliver a constant background flow throughout the respiratory cycle. A difference in the flows in the inspiratory and expiratory limbs (due to patient inspiratory effort) is detected by the flow sensor in the expiratory limb and an increased flow (a breath) is delivered. Flow triggering reduces the work of breathing when compared to pressure triggering because there is always some background flow and no delay due to inspiratory valve opening. The pressure or flow threshold required to trigger a breath can be set by the operator (trigger sensitivity). Low trigger sensitivity can result in breath delivery due to factors other than true patient effort, such as cardiac pulsation or simple movement of the breathing circuit.

Delivery of gas

Modern anaesthetic rooms and intensive care units in the UK will have electronically controlled servo-driven piston ventilators which provide accurate performance and a range of ventilatory modes. Alternatively, a turbine may drive gas through the system, with pressure and flow controlled via valves. However less complex ventilators are still in widespread use in many clinical settings throughout the world.

Minute-volume divider

Older theatre ventilators (e.g. the 'Blease Manley MP5') are driven by the anaesthetic gas supply and supply only that gas (the minute volume), dividing it into preset tidal volumes at a programmed rate. Despite their appearance, they are pressure generators (Figure 2).

Figure 2 The Blease Manley ventilator.

'Bag-in-a-bottle'

IPPV in a circle system may use an ascending bellows filled with anaesthetic gas. The bellows are enclosed in a chamber (adult volume 1500 ml, paediatric 400 ml). Driving gas from the ventilator enters the chamber (always remaining separate from the anaesthetic gas) and forces the bellows down, pushing anaesthetic gas into the inspiratory limb. Controls are simple, usually V_T, respiratory rate (f), I:E ratio (ratio of inspiratory time to expiratory time), airway pressure and an on/off switch (Figure 3).

Pneumatically driven

An example is the 'Penlon Nuffield 200' ventilator which delivers a preset volume to the patient utilizing a driving gas which is either air or oxygen at around 400 kPa. The control unit has a pressure gauge, controls to set inspiratory and expiratory time (seconds) and inspiratory flow rate (l/s). Flow is directed through the ventilator by spool valves using 'fluid logic' (an application of the Coanda effect). A small tube connects the valve block to an airway pressure monitor and a ventilator alarm. The valve block has a port to connect to the breathing system (e.g. Bain) and an exhaust port which can be connected to the scavenging system,

Figure 3 Intermittent positive pressure ventilation in a circle system.

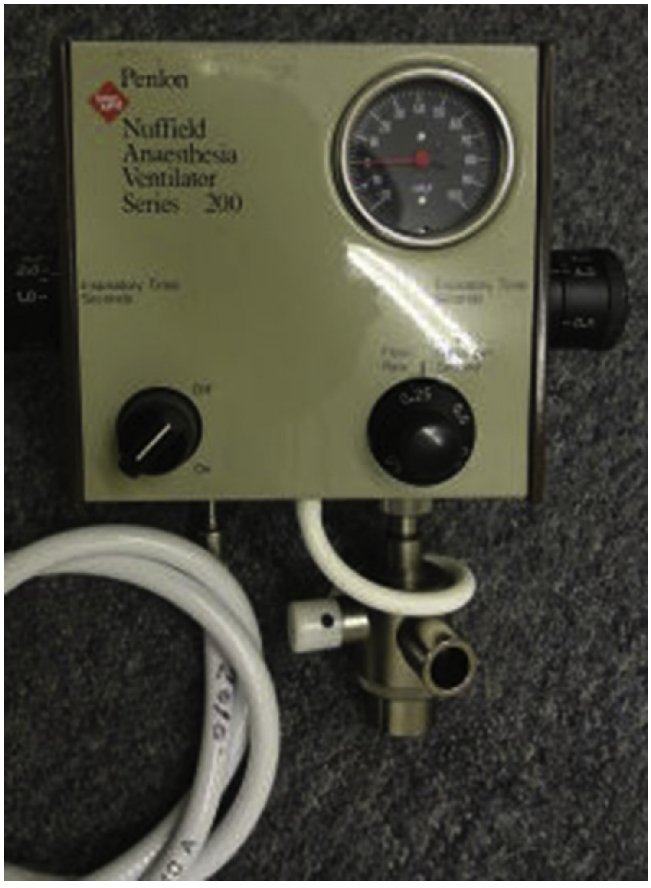

Figure 4 The Penlon Nuffield 200 ventilator.

and a pressure-relief valve which opens at 6–7 kPa. In this configuration it is a time-cycled flow generator (Figure 4).

Transport ventilators

Must be small and lightweight, with minimal requirements for electricity and gases. Most, such as the Oxylog 3000, use oxygen via a cylinder as the driving gas and have a battery which lasts 2–3 hours. They have an increasing number of ventilatory modes but may not deliver the dialled settings as accurately as the static ventilators. For this reason, a trial on the transport ventilator prior to departure is mandatory as is close monitoring of oxygenation and end-tidal CO_2 ($ETCO_2$).

Piston driven/turbine driven

Modern anaesthetic machines (e.g. Dräger Primus) and ITU ventilators are far more complex. They perform automatic self-tests using dual-core processor technology, have a wide range of ventilatory modes and sophisticated spirometry allowing real-time display of flow-volume loops and automatic compensation for leaks and changes in patient compliance. Accurate inspiratory volumes can be delivered by a piston or turbine driven by mains electricity; volume corresponds to distance moved by the plunger along the cylinder. Delivery of programmed parameters is ensured by the use of servomechanisms.

Venturi injector device (jet ventilation)

Consists of a high-pressure oxygen source (about 400 kPa from the pipeline or anaesthetic machine), an on/off trigger and some high-pressure tubing. The Manujet has a dial to alter the driving pressure and can deliver gas via the ventilating port of a bronchoscope, through a tracheostomy, or via a large-bore cannula (in CICV scenarios, for example). The Venturi effect is based on the Bernoulli principle; air is entrained into the lungs due to the area of low pressure created by manually activating the 'Manujet'. Complications include barotrauma (pneumothorax), hypoxia and awareness if inadequate anaesthetic gas delivery is not achieved and alternative intravenous anaesthesia is not delivered. Gas must be able to escape through the upper airway, as expiration via the cannula is impossible.

Apnoeic ventilation

Recent papers have shown renewed interest in 'apnoeic ventilation', maintaining an open airway using airway manoeuvres and high-flow nasal oxygenation systems. Humidified oxygen delivered at rates of 50–70 l/min via nasal cannulae provided sufficient PEEP to maintain open airways, allowing O_2 and CO_2 exchange via diffusion. On average, $PaCO_2$ rose at only 0.15 kPa/min, much less than you would expect, so some augmentation of gas exchange must be occurring. Prolonged apnoeic periods of around 30 minutes with normal blood gases have been reported in small groups. Other studies have shown less promising results. This technique is likely to become more prevalent in theatre in the next few years.

Indications for mechanical ventilation

Mechanical ventilation may be required to treat acute respiratory failure, to protect the airway from aspiration, to reduce the work of breathing in situations where compliance is decreased or oxygen requirements are increased such as in shock (cardiogenic or septic) or to regulate arterial partial pressure of CO_2 ($PaCO_2$) in patients with brain injury and raised ICP.

Respiratory failure may manifest as hypoxaemia (type 1), defined as an arterial partial pressure of oxygen (PaO_2) of <6.7 kPa on air, and/or hypercapnia (type 2), defined as an arterial partial pressure of carbon dioxide $PaCO_2$ of >6.7 kPa.

Hypoxia predominates in conditions such as pulmonary oedema, aspiration, pneumonia and atelectasis, and is often due to ventilation/perfusion ($\dot{V}/\dot{Q}$) mismatch and shunt. Increasing the fraction of inspired oxygen (FiO_2) will not reverse hypoxaemia due to shunt. Rather, improvement will be seen by opening atelectatic areas of lung (recruitment), preventing airway closure (de-recruitment) and increasing cardiac output if low.

Hypercapnia is caused by inadequate alveolar minute ventilation (V_A) due to low tidal volume (V_T) or low respiratory rate (f). Hypercapnia normally stimulates increased V_A so type 2 respiratory failure implies a deficit in one or more of the following areas:

- brain (respiratory drive blunted by sedatives, opioids, brainstem pathology)
- nerve (impairment of transmission in spinal cord injury, Guillain-Barre syndrome, neuromuscular blockade)
- respiratory muscle (inadequate power due to fatigue, dystrophy)
- chest wall (movement restricted by kyphoscoliosis, obesity, rib fracture)

- lung (high airway resistance in obstructive conditions such as chronic obstructive pulmonary disease (COPD), asthma).

Decision to commence mechanical ventilation

The aims of mechanical ventilation are to maintain oxygenation and alveolar ventilation, to reduce the work of breathing (WOB), while maximizing patient comfort and minimizing the chance of ventilator-associated pathology. Commencement is ultimately at the discretion of the clinician following overall assessment of the patient. However, the presence of the following features would suggest that mechanical ventilation is likely to be necessary:

- Severe hypoxaemia (PaO_2 <8 kPa) and/or respiratory acidosis (pH <7.2) despite high-flow oxygen and treatment of the underlying condition.
- Altered mental state (agitation, coma)
- Excessive work of breathing/exhaustion (tachypnoea, nasal flaring, accessory muscle use)
- Signs of excessive catecholamine release (diaphoresis, tachycardia, hypertension)

A similar assessment would be made when deciding that a patient has failed a trial of weaning and needs recommencement of respiratory support.

Ventilator modes

The commonly used modes are summarized in Table 1.

Volume-control modes will tend to deliver a reliable V_T, but airway pressure will vary with compliance and resistance. They are used in situations where $PaCO_2$ must be within tight limits, and airway pressure is of secondary importance (for example, in a head-injured patient with no lung injury). Older ventilators would cease flow once the set peak pressure (P_{peak}) had been reached, limiting V_T. More recently, flow will continue at the peak pressure for the remainder of the inspiratory phase, maximizing V_T in uncompliant lungs.

Pressure modes limit airway pressure, reducing the possibility of barotrauma, but volutrauma is still a risk. The decelerating inspiratory flow pattern may improve gas-exchange and improves patient comfort. However, despite the theoretical advantages of pressure control there is no firm evidence that it changes outcome.

Modern dual modes attempt to combine the best features of pressure and volume control. A target volume will be delivered as a square wave of pressure, giving a reliable V_T but minimizing P_{peak}. It takes the ventilator several breaths to adapt to changes in compliance, so V_T can vary in this time. In all modes, appropriate

Commonly used ventilator modes

Mode	Advantages	Disadvantages
Volume modes		
CMV (continuous mandatory ventilation): Ventilator delivers breaths at a set rate and V_T	Complete rest of respiratory muscles. Used mainly in theatre	No allowance for patient triggered breaths Requires deep sedation and muscle relaxation
A/C (Assist-control): V_T is the same whether time-triggered or patient (pressure or flow) triggered	Maximum reduction in WOB (useful if respiratory weakness or LV failure). Patient can increase RR	Triggering of breaths prior to full exhalation can cause hyperventilation, breath-stacking, high airway pressures (hence hypotension)
SIMV (synchronized intermittent mandatory ventilation). In volume-control mode, delivers fixed number of mandatory breaths of fixed V_T, synchronized with patient efforts	Mandatory breaths time-triggered if no respiratory effort (guaranteed minimum minute volume). Spontaneous breaths may be pressure-supported	Caution when setting (fixed) inspiratory flow-too high causes high peak pressure (P_{peak}), too low causes flow starvation (patient discomfort)
Pressure modes		
SIMV (pressure control): Mandatory breaths deliver a pressure rather than volume	Decelerating flow profile limits P_{peak} and may improve gas-exchange	Variable V_T if compliance changes, PaC02 variable
PS (pressure-support): Patient determines rate and flow, ventilator augments with set pressure	Patient comfort, useful for weaning. WOB can be reduced by increasing PS	Needs normal ventilatory drive. Flow-cycled (no inspiratory pause) may inhibit gas-exchange
BIPAP (bilevel positive airway pressure):Time-cycled between two adjustable levels of continuous positive airway pressure (CPAP)	Spontaneous breaths possible at both levels at all times	Minute ventilation variable
APRV (airway pressure release ventilation): Like BIPAP with most time spent at higher pressure	Mean pressure can be raised if refractory hypoxaemia/hypercapnia in acute respiratory distress syndrome (ARDS)	High mean pressures may reduce cardiac output (CO) and blood pressure
PCIRV (pressure-control inverse ratio ventilation): Like APRV in absence of spontaneous breaths	I:E ratio can be changed from normal 1:3, to eg 3:1, raising mean airway pressure and oxygenation	Short expiratory may not be adequate for full expiration resulting in dynamic hyperinflation
Dual modes		
Include Autoflow, PRVC (pressure regulated volume controlled)	Set tidal volume delivered with decelerating inspiratory flow, reducing P_{peak} and greater patient comfort	Ventilator may not keep pace with compliance/resistance changes in unsedated patient, leading to variable V_T

Table 1

alarms must be set to alert the clinician to excessive P_{peak}, small or large expired volume (V_E) and minute volume (V_E) and respiratory rate (f) (Figure 5).

Positive end expiratory pressure

In normal respiration, we exhale to atmospheric pressure (zero). During artificial ventilation, particularly in disease states such as pulmonary oedema and ARDS, it may be beneficial to increase the pressure in the expiratory limb to above zero, known as positive end expiratory pressure (PEEP). In normal breathing this is achieved by the partial relaxation (closure) of the vocal cords in expiration, or by pursing of the lips causing autoPEEP (see below). In the ventilated patient it is achieved with a restrictive valve on the expiratory limb of the ventilator. PEEP is usually set between 0 and 20 cmH_2O. The back-pressure of PEEP can 'splint' airways open during expiration and open atelectactic areas, especially in dependent areas (recruitment). This improves $\dot{V}/\dot{Q}$ matching and reduces shunt, therefore increasing oxygenation. In heart failure, the reduction in venous return due to PEEP may push the ventricles into a more favourable part of the Frank-Starling curve, thus improving cardiac output.

Optimum PEEP can be set with reference to the static compliance curve. At low lung volumes (below closing volume), alveoli, particularly in dependent areas, are collapsed. Additional work is required to open these areas and thus a higher distending pressure is required for a given volume (lower compliance). At high lung volumes, the elastic lung tissue is already distended so higher pressures are required for a given distension. A static curve can be plotted with pressure-control ventilation by changing V_T every 5 breaths and monitoring plateau pressure (when flow has ceased) against volume. Some ventilators are able to calculate a static compliance curve. With this information, PEEP can be set so that functional residual capacity (FRC) is higher than closing capacity, optimally at the lower inflection point of the static compliance curve (Figure 6).

The closing capacity (CC) is that degree of lung expansion below which small airways, particularly in dependent areas, begin to collapse. It is the sum of the residual volume and the closing volume. The functional residual capacity (FRC) is reached when the expanding force of the chest wall is balanced by the elastic recoil of the lung at the end of unforced expiration. FRC is higher than closing capacity in young, healthy, awake individuals; therefore CC is not encroached upon during a normal V_T. General anaesthesia reduces FRC by relaxing the diaphragm and intercostal muscles (with or without neuromuscular blocking drugs), so during tidal breathing FRC is more likely to reduce below CC causing airway collapse and $\dot{V}/\dot{Q}$ mismatch. FRC is further reduced by the supine position and conditions which compress the lung such as obesity, pregnancy and intra-abdominal hypertension. Therefore PEEP combined with a head-up position (30 degrees) is useful in most patients

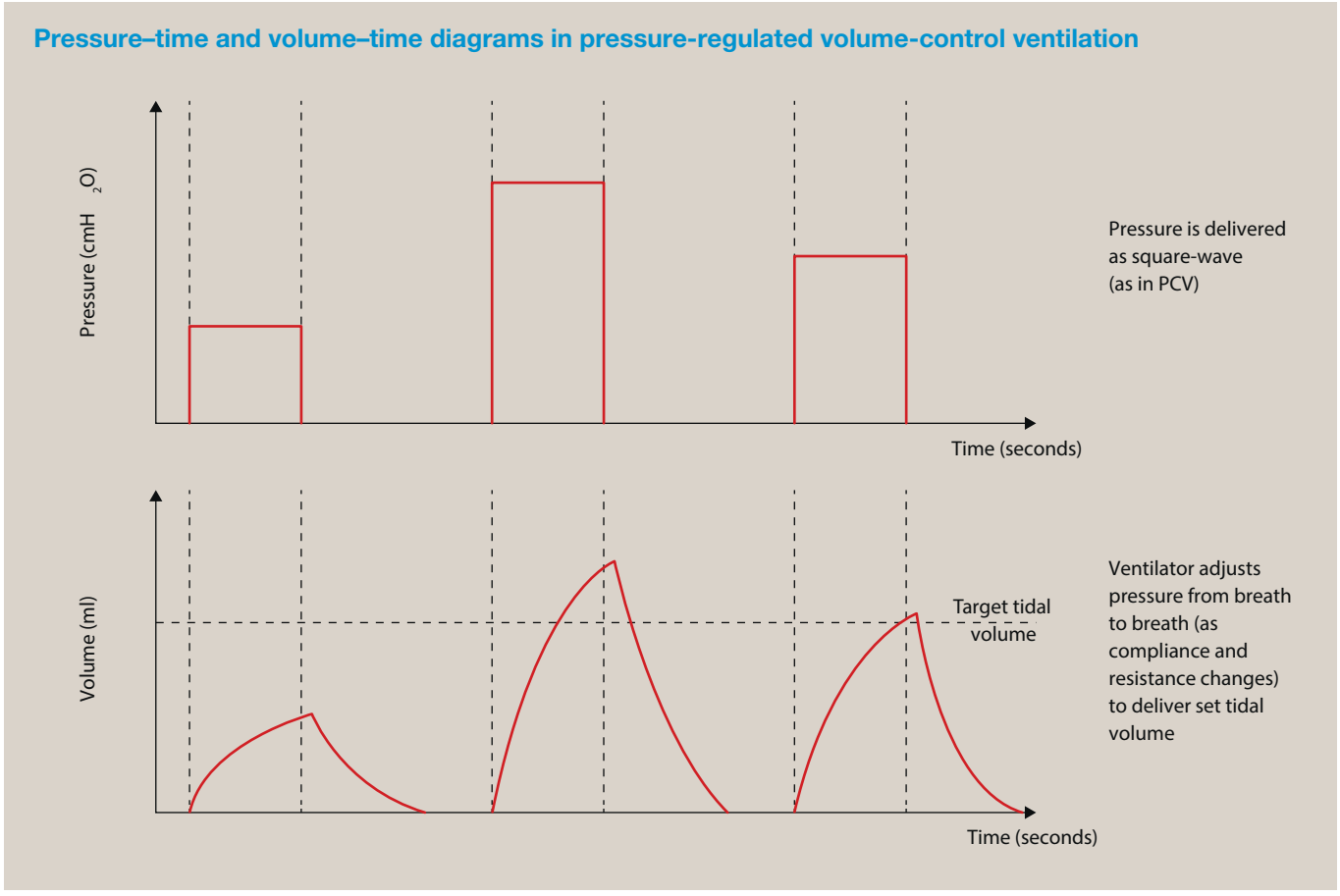

Figure 5

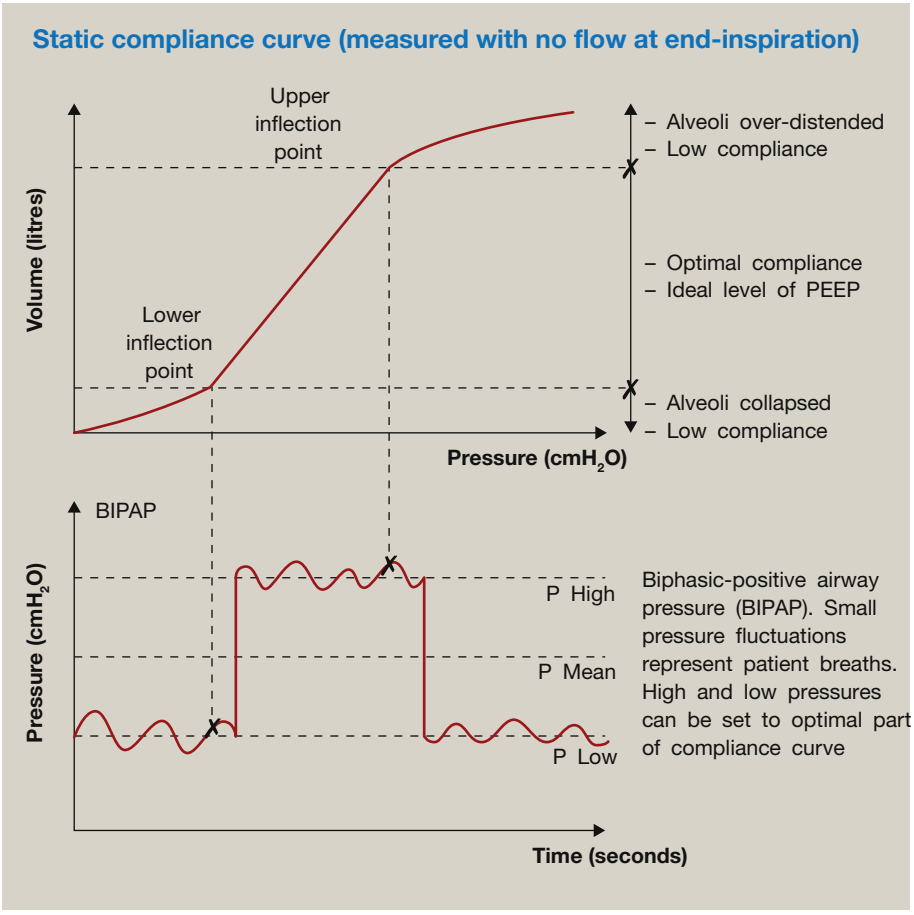

Figure 6

who are ventilated in the intensive care unit, especially in conditions which reduce the FRC. Dependent areas receive a greater proportion of pulmonary blood flow (they have lower V/Q ratios) and recruitment of these areas can cause a significant increase in oxygenation by reducing the shunt fraction (the proportion of pulmonary blood flow which reaches the left atrium without participating in gas exchange).

Excessive PEEP can cause over-distension and increased dead space. PEEP should therefore be titrated in a trade-off between increasing V_D and decreasing shunt (Figure 7). By raising mean airway pressure, hypotension can be exacerbated. The impedance of venous return and transmission of pressure to the cerebrospinal fluid can raise intracranial pressure so PEEP should be used cautiously when managing acute brain injury. However, patients

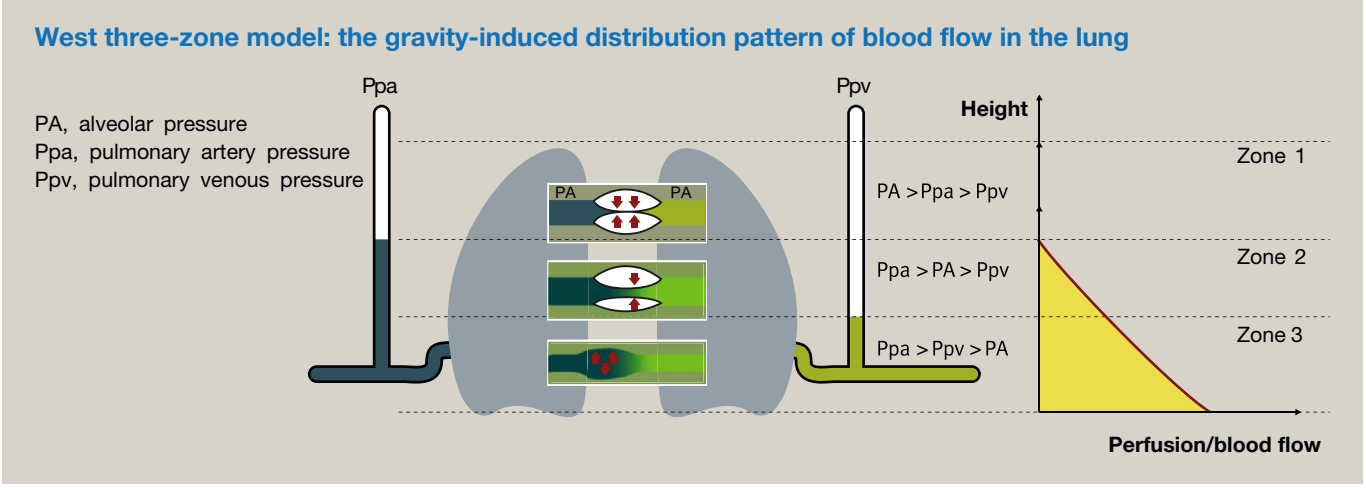

Figure 7

with low lung compliance (as in ARDS) will benefit from PEEP, and the negative effects on the brain will be slim if the normal brain-protective strategies are used. Patients with low intracerebral compliance (cerebral oedema, high ICP) *are* at increased risk from the negative effects of PEEP, and the lung-protective ventilation strategy may have to be modified. At low mean intrathoracic pressures, distribution of perfusion remains normal during artificial ventilation. Non-dependent areas have a lower capillary pressure and are therefore relatively under perfused (high $\dot{V}/\dot{Q}$ ratio) due to the effect of gravity on the low pressure pulmonary circulation. If pressures exceed 30 cmH_2O, perfusion is reduced further by compression of pulmonary capillaries.

Effects of artificial ventilation on body systems

Heart–lung interactions

In spontaneous ventilation, negative intrathoracic pressure tends to augment venous return (the thorax 'sucks' blood toward the right atrium on inspiration). In IPPV, the situation is reversed. Intrathoracic pressure is transmitted to the low pressure right atrium, impeding venous return and reducing preload and therefore right ventricular output. As the left and right ventricles are in series, left ventricular preload is also reduced. The reduced stroke volume leads to a reduced cardiac output and lower mean arterial pressure.

Pulmonary vascular resistance (PVR)

PVR is increased at the extremes of lung volume. At low lung volumes, small airways collapse and the radius of pulmonary blood vessels decreases as the outward distending force is no longer present. At high lung volumes the combination of increased intrathoracic pressure and distortion of pulmonary vasculature reduces vessel radius, increasing resistance to flow. Hypoxia and hypercapnia (in conditions such as COPD) cause further rises in PVR due to hypoxic vasoconstriction. High PVR raises pulmonary arterial pressure for a given cardiac output (CO) and in the face of pulmonary hypertension, the right ventricular end diastolic volume (RVEDV) will increase, maintaining CO. This dilatation can be compounded by myocardial ischaemia, as raised RV pressures reduce coronary perfusion pressure. As the RV starts to fail, it will dilate further. This increase in volume can impinge directly on the left ventricle (LV), causing compression and reduced left ventricular end diastolic volume (LVEDV), a phenomenon known as ventricular interdependence. The stroke volume of the compressed LV will fall, causing reduced CO in a manner similar to cardiac tamponade.

Patients with pre-existing heart failure

In this state, the reduced preload due to IPPV may place the LV on a more favourable part of the Frank-Starling curve and therefore increase cardiac output. In patients with raised RVEDV (e.g. cor pulmonale) the reduced preload may reduce RVEDV, reducing compression of the LV, facilitating LV filling and improving CO. Intrathoracic pressure can also be directly transmitted to the LV and thoracic aorta, reducing the work of the LV to maintain a given systolic pressure.

In summary, the cardiovascular effects of artificial ventilation will vary depending on the basal cardiovascular status of the patient, respiratory pathophysiology and the mode of ventilation.

Kidney

In IPPV, the reduced CO will result in reduced mean arterial pressure (MAP). Low-pressure baroreceptors will activate less frequently, resulting in increased sympathetic activity, activation of the renin-angiotensin-aldosterone system and release of vasopressin. In addition, reduced right atrial pressure due to reduced venous return will be sensed by stretch receptors in the right atrium causing a reduction in atrial natriuretic peptide (ANP) release. The combined effect of these hormones is sodium and water retention by the kidney. The combination of reduced renal perfusion pressure and venous congestion due to raised intrathoracic pressure may reduce glomerular filtration rate and exacerbate an acute kidney injury.

Liver

Hepatic perfusion is dependent on CO and MAP, which tend to fall during artificial ventilation. Sixty percent of hepatic perfusion is via the low-pressure portal vein. Raised intrathoracic pressure can cause venous congestion in the liver as the higher pressure in the hepatic veins reduces the pressure gradient for flow through the liver. Hypoperfusion may result in reduced function of hepatocytes, especially in critically ill patients with co-morbidities.

Brain

Raised intrathoracic pressure can impede venous drainage of the brain. Increased intracerebral venous volume can result in raised intracranial pressure (according to the Monroe–Kelly doctrine). In combination with a fall in MAP, this can reduce cerebral perfusion pressure (CPP). A normal brain will maintain perfusion over a large range of CPP via autoregulation. In disease states (such as traumatic brain injury and meningitis), autoregulation can be impaired and cerebral hypoperfusion may ensue. PEEP is routinely used in the ventilated patient but should be treated with caution.

Mechanical ventilation in specific disease states

Chronic obstructive pulmonary disease and asthma

These two diseases represent opposite points on the spectrum of obstructive lung disease, COPD being irreversible airway obstruction and asthma being reversible obstructive disease. In reality there may be some degree of reversibility in COPD hence the efficacy of bronchodilators. Medium-sized bronchioles in particular are narrowed by bronchospasm, inflammation and mucus plugging. Resistance is inversely proportional to the fourth power of the radius during laminar flow and airway resistance is therefore greatly increased in these conditions. Airway radius is increased at high lung volumes due to pronounced sub-atmospheric intrapleural pressures, so patients with COPD tend to breathe using small tidal volumes and a high FRC (hyper-expanded chest).

During inspiration, normal flow rates and volumes would require high driving pressures to overcome the airway resistance. This increases the risk of barotrauma, so lower V_T with P_{peak} <30 cmH_2O is aimed for. Adequate oxygenation with pO_2 >8 Kpa can usually be achieved by increasing the FiO_2 and cautious use of PEEP.

Gas trapping: expiration usually presents more of a problem than inspiration in obstructive conditions. In inspiration, low

flow rates due to narrowed bronchioles can be partially overcome by increased sub-atmospheric intrapleural pressures in spontaneous breathing or higher inspiratory pressure in IPPV. As the thoracic volume increases, the cross-sectional area of the bronchioles increases, reducing resistance. During expiration, whether passive or active, flow is proportional to the pressure gradient between alveoli and mouth (the mouth normally being at atmospheric pressure). When a fluid flows through a pipe, pressure drops along its length in proportion to the resistance. In obstructive conditions, airways resistance is greater, therefore the pressure drop is more pronounced. There comes a point between alveoli and mouth where intrapleural pressure and intraluminal (bronchial) pressure are equal. More proximal to this (closer to the mouth) the airways will be closed as intrapleural pressure is higher than intraluminal pressure. The gas distal to this point is therefore trapped, a problem which cannot be remedied by increasing intrapleural pressure (effort independent flow restriction). The trapped gas means that at end expiration, airway pressure in this section of the airway does not fall to zero; this increased pressure is known as intrinsic PEEP, auto-PEEP or PEEPi. This can be measured on a ventilator by measuring the pressure during an end-expiratory hold and subtracting applied PEEP from this value. Auto-PEEP increases the WOB as intra-pleural pressure must overcome auto-PEEP before flow occurs. Therefore cautious-wise addition of a small amount of external PEEP may help.

Dynamic hyperinflation: the high airways resistance means that lung units in obstructive conditions have long time constants (time constant [τ] = resistance [R] $\times$ compliance [C]) so inspiration, and particularly expiration, of a given V_T requires more time. During mechanical ventilation, if sufficient expiratory time is not allowed the next inspiration will be delivered before full expiration has occurred. This can be seen on the ventilator flow-time display when expiratory flow does not return to zero (Figure 8); with each subsequent breath, lung volume will increase. This is known as breath-stacking or dynamic hyperinflation. The hyper-expanded lungs are now in the flattest part of the static compliance curve, so distending pressures increase, V_T falls, and V_D increases resulting in reduced gas exchange. The high intrathoracic pressures also decrease venous return, causing a fall in cardiac output and hypotension. The solution is to allow sufficient expiratory time by choosing a low rate and reducing the I:E ratio until it can be seen that expiratory flow has ceased prior to inspiration. If this fails, manual decompression may be performed; the patient is disconnected from the circuit allowing the lung to deflate over several seconds.

In COPD, a trial of non-invasive positive pressure ventilation (NIPPV) is often used – studies have shown that this decreases the need for mechanical ventilation, so decreasing mortality. BiPAP (bi-level positive airway pressure) is the mode most commonly used. Whether NIPPV or IPPV is used, the optimum mode would be spontaneously breathing pressure-support. In both conditions, the highly reactive airways may cause breath-holding and coughing to the extent that adequate ventilation is impossible despite maximal bronchodilator therapy. In this case, a period of muscle paralysis and pressure-control ventilation may be necessary.

Acute respiratory distress syndrome (ARDS)

ARDS is defined as 'an acute inflammatory syndrome manifesting as diffuse pulmonary oedema and respiratory failure that cannot be explained by, but may co-exist with, left-sided heart failure'. It can occur as a result of primary injury to the lungs or as a secondary consequence of a systemic disease. Aims of therapy are to maintain near-normal respiratory physiology while preventing injury to the lung as a consequence of ventilation.

Ventilator-associated lung injury:

Volutrauma – ARDS usually manifests with heterogeneous lung changes, with areas of diseased lung adjacent to relatively normal areas, hence the characteristic patchy 'fluffiness' from infiltrates on the CXR. Diseased areas suffer from direct endothelial damage, lack of surfactant, release of inflammatory mediators and leucocyte activation. This leads to capillary leak, causing localized pulmonary oedema. Diseased lung units therefore have reduced compliance, long time constants and atelectasis. During any delivered breath, gas will flow more slowly into diseased areas, and due to the law of Laplace smaller alveoli will empty into larger ones. The ventilated breath is therefore delivered preferentially to the remaining areas of healthy lung. This small, healthy lung volume (the so-called 'baby lung') receives a proportionally large V_T, resulting in endothelial over-distension stretch and further lung injury. In other ARDS patients, lung injury is more homogeneous. The patients with heterogeneous changes are at greater risk of volutrauma (Figure 9).

Barotrauma – injured lungs, when exposed to positive pressure, are more likely to be perforated, leading to extrapulmonary air (pneumothorax, mediastinal emphysema, subcutaneous emphysema). High airway pressures increase this risk.

Atelectrauma – the damage caused by repeated collapse and re-inflation of lung units (repeated cycles of recruitment/de-recruitment). Positive end expiratory pressure limits this by preventing small airway collapse.

Biotrauma – the additional damage caused by release of inflammatory mediators such as TNF-alpha, IL-6 and complement. This may not be an individual injury as much as a consequence of volutrauma and atelectrauma.

Lung-protective ventilation: the aim in ARDS is to maintain oxygenation and CO_2 levels within acceptable limits while minimizing ventilator- associated lung injury. The ARDSnet group demonstrated through randomized controlled trials that survival is increased when ventilation is limited to 6 ml/kg (as opposed to 12ml/kg). In addition, they have produced a protocol which is widely used involving calculation of the patient's ideal body weight and starting with a V_T of 6 ml/kg. PEEP is adjusted according to the required FiO_2 (see Table 2). Excessive hypercapnia can then be managed by increasing rate rather than V_T, although *permissive hypercapnia* is tolerated provided the pH is >7.25. Refractory hypoxia can be managed by increasing FiO_2, or mean airway pressure, which may be achieved in a number of ways.

A higher mean airway pressure for a given P_{peak} is achieved with pressure-control ventilation. Normal alveoli are susceptible to high P_{peak}, which should be kept below 35 cmH_2O. This can be

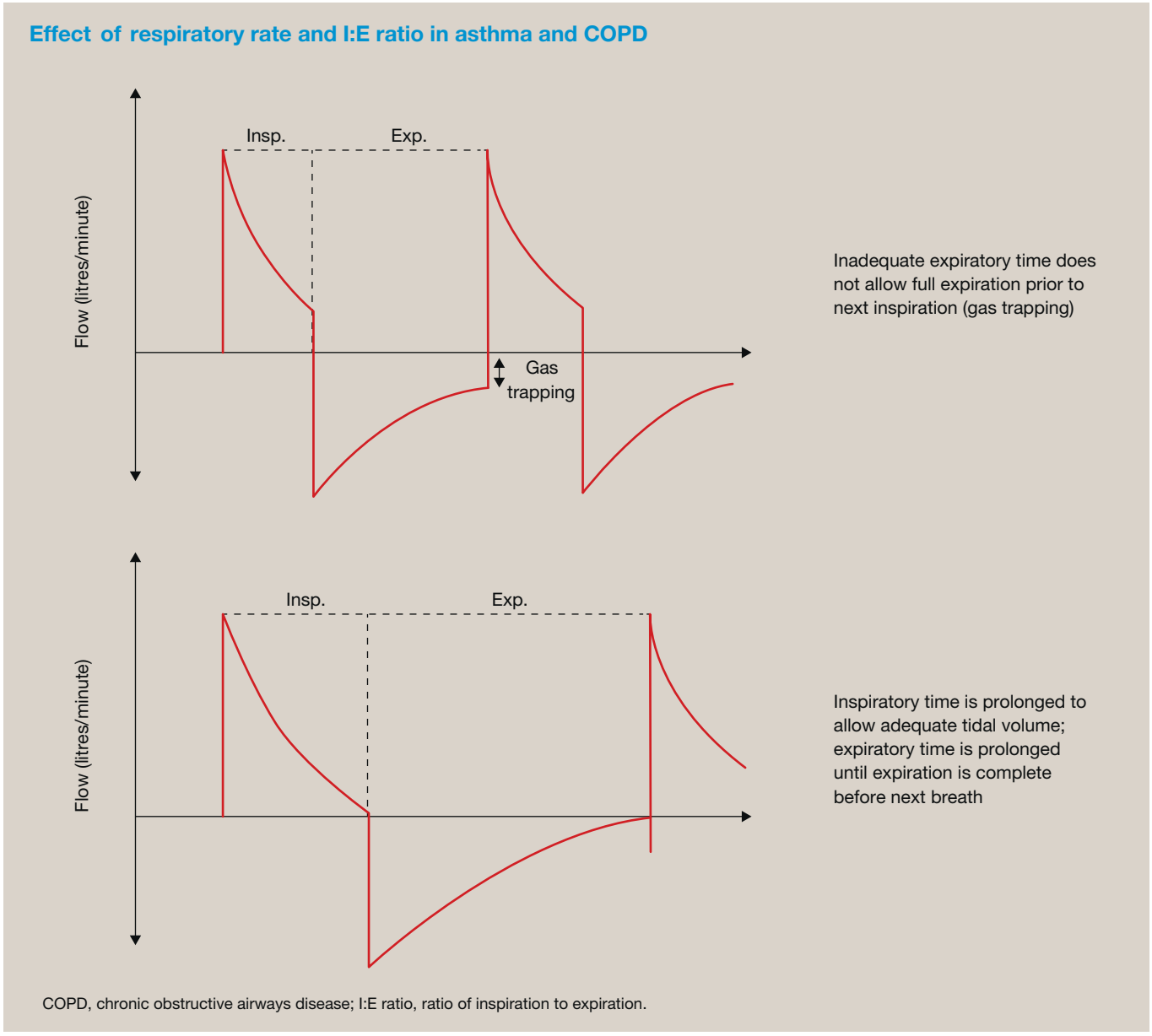

Figure 8

difficult to achieve in volume-control ventilation due to the non-compliant lungs. In pressure-control mode, prolonging the inspiratory time (higher I:E ratio leading to inverse-ratio ventilation when inspiratory time is greater than expiratory time) increases mean pressure without altering P_{peak}. Reduced expiratory time may mean inspiration begins before full expiration, leading to gas-trapping. To remedy this, attention should be paid to the real-time graphical displays of pressure and flow waveforms on the ventilator. The respiratory rate and I:E ratio can be reduced until the waveform shows that expiratory flow has ceased prior to the next inspiration. If gas trapping occurs in pressure-control mode, progressive hyperinflation will ensue leading to progressive reduction in V_T (as compliance decreases at high lung volumes). In volume-control mode, the V_T would be maintained with a progressive increase in P_{peak}, which will worsen gas trapping. Therefore volume control should not be used with inverse-ratio ventilation.

Recruitment manoeuvres

Refractory hypoxaemia can be temporarily improved by opening up atelectatic areas of lung. This can be achieved manually by gradually delivering breaths of increasing volume over 5–10 breaths, with a PEEP of around 15 cmH_2O; the same can be achieved with a ventilator. Alternatively, a fixed high level of PEEP of 20–30 cmH_2O can be applied for 20–30 seconds. The sustained intrathoracic pressure may impede venous return causing hypotension, in which case the manoeuvre should be terminated. There is no evidence that these manoeuvres affect long term outcome, and they may contribute to volutrauma.

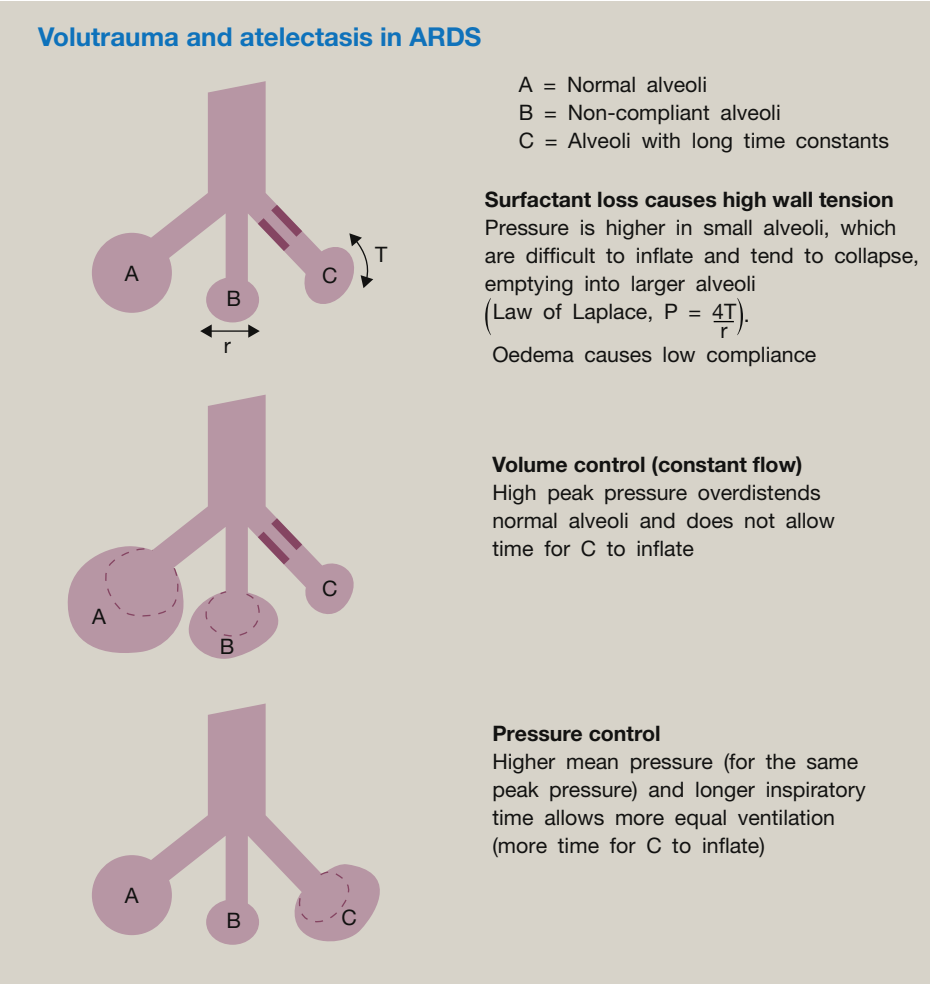

Figure 9

Prone ventilation: ventilation in the prone position improves oxygenation in 50–75% of ARDS patients. Positive pressure ventilation preferentially ventilates non-dependent areas of lung (anterior and apical areas in the supine patient). The prone position leads to recruitment of postero-basal areas of lung. The perfusion pattern remains relatively constant whether supine or prone, and postero-basal areas have proportionally greater perfusion so $\dot{V}/\dot{Q}$ matching can be improved. Compressive atelectasis due to the weight of the heart is alleviated as the heart is now dependent, further aiding recruitment.

Extra-corporeal membrane oxygenation (ECMO): if hypoxaemia and/or hypercapnia is refractory despite the above measures, ECMO may be considered to perform gas exchange while allowing lung-protective ventilation to continue. It may be best applied early in severe ARDS. It is expensive, highly invasive, has a high complication rate and will usually involve the risks of an inter-hospital transfer of a critically ill patient. There is limited evidence that it improves outcome.

High-frequency oscillation ventilation (HFOV): taking low tidal volume ventilation to a greater extreme, HFOV uses a special ventilator (e.g. the 'Novalung R100') to deliver tiny tidal volumes (around 1 ml/kg) at rates of 600–900 breaths/min, with mean airway pressures sufficiently high to maintain oxygen uptake. Gas movement has been postulated to occur by diffusion, turbulence and pendelluft amongst other mechanisms, as opposed to bulk flow in conventional ventilation. It was hoped that by

Titration of FiO_2 and PEEP in ARDS

FiO_2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1.0
PEEP	5	5	8	8	10	10	10	12	14	14	14	16	18	<24

Oxygenation goal: PaO_2 7.3–10.7kPa or O_2 saturation 88–95% (from www.ARDSnet.org).

Table 2

minimizing changes in lung volume, volutrauma would be reduced in ARDS. However, two large trials comparing HFOV and conventional ventilation were published which appeared to sound the death knell for HFOV in ARDS. OSCILLATE was stopped early due to a markedly higher mortality rate in the HFOV group and OSCAR (in the UK) demonstrated no difference in outcome with the two modalities. Some believe there may still be a place for HFOV in certain subgroups of ARDS, but evidence is lacking.

Extra-corporeal carbon dioxide removal (ECCOR): reducing tidal volume during artificial ventilation in patients with ARDS will minimize volutrauma as described above, but it will almost inevitably lead to hypercapnia. In many patients this is accepted provided the patient's pH remains above 7.25 kPa, but in some circumstances arterial CO_2 can rise substantially due to an imbalance between production and clearance. It is now possible to remove arterial CO_2 via an extracorporeal device that is inserted via a veno-venous route, e.g. The Novalung. ECCOR has not been demonstrated to improve mortality in two small trials although a major randomized controlled trial is currently underway.

Minimizing harm

Other adverse effects of artificial ventilation include oxygen toxicity, which is thought to begin after 24 hours of ventilation with FiO_2 greater than 0.6. The lowest FiO_2 should be used for the shortest time possible. Ventilator-associated pneumonia (VAP) occurs at a rate of around 1% per day and may result in increased mortality. Intuitively, late-onset VAP (more than 96 hours post intubation) should be associated with a higher incidence of multidrug-resistant organisms and therefore higher mortality, though studies have not confirmed this suspicion. Meticulous aseptic technique, elevation of the head of the bed, non-nasal intubation and adequate nutrition reduce the incidence of VAP. Endotracheal tube (ETT) cuff pressure monitoring, specialist cuff design and tubes with subglottic suction also contribute to a reduction in VAP. Appropriate antibiotic stewardship reduces the incidence of colonization with multidrug resistant organisms.

Troubleshooting

Peak pressure alarms present a common diagnostic problem in the ventilated patient. Low P_{peak} is usually due to an air leak or disconnection. High P_{peak} may represent reduced compliance or increased airway resistance, which can be differentiated by clinical examination and by performing an inspiratory hold manoeuvre. High P_{peak} with a normal plateau pressure suggests increased airway resistance. An increase in both suggests reduced compliance. Figure 10 lists conditions which need to be considered in each case.

Weaning from ventilation

Given the potential harm associated with artificial ventilation, attempts should be made towards liberating the patient from the ventilator as soon as the pathology which necessitated artificial ventilation has started to improve. The requirement for continued mechanical ventilation should be reviewed daily. Weaning involves identifying those patients who can breathe spontaneously and maximizing the chance of successful extubation as re-intubation after premature extubation has associated morbidity including increased incidence of VAP and increases mortality.

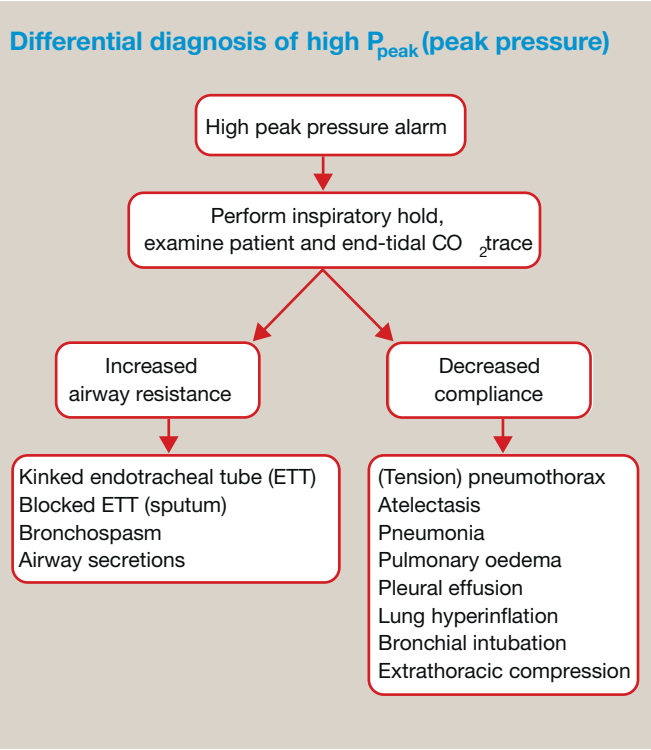

Figure 10

The decision to extubate is again an individualized clinical decision; there is no single predictive test or combination of tests which will predict success with 100% accuracy. Clinicians assess a range of parameters that identify a patient as suitable for weaning and use simple bedside tests as an aid to decision-making. The patient should be able to maintain gas exchange with a low PEEP (5 cmH_2O or less) and FiO_2 less than 0.5, with a minute ventilation of less than 20 l/min. Patients should be co-operative and alert. Reduced conscious level due to excessive sedative and opioid use delays weaning and should be avoided by regular monitoring of sedation requirements (tools such as the Richmond Agitation Sedation Score may be used). Daily sedation breaks are associated with a reduced duration of mechanical ventilation. Haemodynamic stability should be present with a low or reducing requirement for inotropes and vasopressors. Electrolyte derangements such as hypokalaemia, hypomagnesaemia and hypophosphataemia should be corrected as they are associated with muscle weakness. Ventilatory requirement is increased by pyrexia and excessive carbohydrate administration which may contribute to weaning failure.

Predictive tests

Markers of respiratory function such as vital capacity less than 10 ml/kg or maximum inspiratory pressure less than 20 cmH_2O

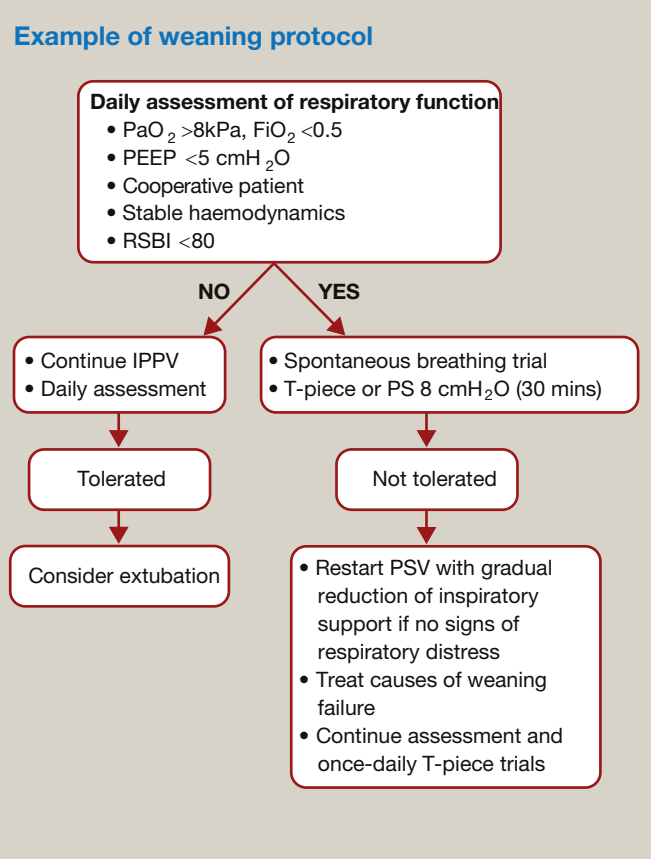

Figure 11

indicate that a patient has adequate respiratory muscle strength, but the tests can be difficult to perform and do not guarantee success. Rapid shallow breathing is a relatively sensitive and specific predictor of weaning failure. This is assessed during a spontaneous breathing trial or with pressure support set only to overcome tube resistance (e.g. less than 8 cmH_2O). The rapid shallow breathing index is calculated by dividing respiratory rate by the tidal volume (in litres). A figure more than 105 predicts weaning failure in 97% of patients.

Spontaneous breathing trial (SBT)

Once a patient has been deemed suitable, weaning should be performed with a daily T-piece trial or by progressive reduction of inspiratory support during PSV. If a patient can perform 30 minutes of spontaneous breathing on a T-piece or with minimal support, extubation can be considered but success will also depend on their ability to clear secretions and protect their airway. The features which characterize a failed SBT are the same as those which initially mandated mechanical ventilation. Longer T-piece trials do not increase the predictive value and may cause exhaustion, slowing the patient's recovery. An example of a weaning protocol is shown in Figure 11, although protocol-based weaning conducted by non-physicians (nurses or physiotherapists) has been shown to be more effective than physician-guided weaning. ◆

FURTHER READING

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