MECHANICAL VENTILATION

An overview of mechanical ventilation in the intensive care unit


Abstract

This article discusses the history, types and essential components of mechanical ventilation. It addresses the potential complications associated with mechanical ventilation and outlines the nurse’s role in the recognition and prevention of such complications. This article provides an overview of some of the advances in mechanical ventilation and emphasises the importance of patient safety through an awareness of the associated risks and limiting or avoiding mechanical ventilation where possible.

Keywords

critical care, intensive care, mechanical ventilation, negative pressure ventilation, positive pressure ventilation, respiratory function, respiratory system

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MECHANICAL VENTILATION is a method used to artificially support respiratory function by means of a ventilator machine. It can be used to either assist or replace normal spontaneous breathing and can be undertaken invasively or non-invasively. There are several reasons why patients may require mechanical ventilation, its main aim being to correct hypoxia, hypercapnia, physiological stress and/or respiratory failure. These conditions are commonly caused by infection, trauma, sepsis and cardiac failure, or occur in patients who are unable to maintain their airway, for example those with a neurological injury or disease, or under general anaesthetic (Tobin 2013).

Mechanical ventilation is performed for relatively short periods in operating theatres and for longer periods of time in intensive care units (ICUs). It is also performed in specialist ward areas and in the patient’s home. The nurse’s role in the management of a patient on mechanical ventilation is complex and multifactorial, and has been shown to directly affect patient outcomes, including patient-acquired complications such as volutrauma, barotrauma, tracheal injury, ventilator-associated pneumonia and multiple organ failure (Alphonso et al 2004, Burns 2005, British Association of Critical Care Nurses 2010).

Outside the operating theatre, the care of patients on mechanical ventilation is primarily undertaken by intensive care nurses, in collaboration with the multidisciplinary team. Therefore, these nurses require a comprehensive understanding of respiratory mechanics, ventilation theory and the components of mechanical ventilation. Continuous monitoring, ongoing safety assessment and knowledge of the variety of methods used to manipulate physiological parameters are also essential to prevent harm to patients on mechanical ventilation.

Intensive care nurses are ideally placed to promote safe and optimal ventilation because of their role in monitoring the patient’s condition and their continual bedside presence. The knowledge and skills of nurses caring for critically ill patients may directly affect the patient outcomes outlined previously (British Association of Critical Care Nurses 2010). An understanding of
mechanical ventilation may also be useful in areas of healthcare such as emergency departments, high dependency units and anywhere a patient is likely to experience respiratory deterioration.

The simplest type of artificial ventilation is used in emergencies when a patient is in cardiac or respiratory arrest. A trained healthcare professional provides respiration by compressing an ambulatory bag attached to either a tight-fitting face mask or via a supraglottic airway device or endotracheal tube that maintains the patient’s airway. In this case, the healthcare professional compressing the bag regulates breath delivery. While this type of ventilation is adequate in an emergency, ventilation for extended periods will have to be accurately delivered by a ventilator. There are two main types of mechanical ventilation: negative pressure ventilation and positive pressure ventilation.

Types of mechanical ventilation

Negative pressure ventilation

Negative pressure ventilation can be delivered via a machine known as an ‘iron lung’, which was predominantly used in the 1940s and 1950s for patients with polio. The iron lung functioned by augmenting respiratory function. In normal physiological inspiration, negative intrapleural pressure is generated as the ribcage expands and the diaphragm contracts. An expanding chest cavity creates an inward pressure gradient between the atmosphere and the alveoli. The result is that air flows into the lungs (Thomson 1997).

In patients with polio, normal ventilation becomes impaired as a result of respiratory muscle weakness and shrinkage, and paralysis. By enclosing the patient’s body in a cylindrical steel drum with only their head and neck protruding from an airtight seal at one end, chamber pressure switches between positive and negative pressure to mimic conventional respiration. When the chamber is vacuumed (negative pressure), inhalation is facilitated. When this process is reversed with positive pressure, exhalation occurs (Corrado and Gorini 2002).

One advantage of negative pressure ventilation is that it is physiologically complementary to normal breathing, and, because it is delivered from outside the body, it is ‘non-invasive’. However, there are practical challenges for healthcare professionals in providing care and treatment for a patient who is enclosed in an iron casing. The only negative pressure ventilator currently marketed in the UK is the relatively light, portable biphasic cuirass ventilator, which only envelopes the patient's upper torso. Although the biphasic cuirass ventilator may potentially be used in all instances of respiratory failure, in practice it is rarely used (Yamashita et al 2012).

Positive pressure ventilation

Negative pressure iron lungs have been superseded by positive pressure ventilation, which is the direct delivery of forced air and oxygen into the lungs. Positive pressure ventilation can be delivered in two ways: non-invasively via a tight-fitting face or nasal mask; or, more commonly, invasively, via a tube placed in the larynx or trachea. In positive pressure ventilation, normal physiological breathing is bypassed, and oxygen and air is forced into the lungs using a positive pressure generated externally by the ventilator. This enables easier access to the patient compared with an iron lung but has the potential to cause more damage to the delicate lung tissue (Soni and Williams 2008). Figure 1 shows a mechanical ventilator for positive pressure ventilation.

There are several essential components of positive pressure ventilation, including: oxygen and air delivery, respiratory rate, volume and pressure-controlled ventilation, pressure support, positive end-expiratory pressure (PEEP) and continuous positive airway, breath trigger, monitoring and alarms, and humidification.

Components of positive pressure ventilation

Oxygen and air delivery

All ventilators have the ability to deliver a blended percentage of oxygen and air, known as the fraction of inspired oxygen (FiO₂). In extreme cases and emergencies, it
might be necessary to deliver 100% oxygen to the patient, but this should be avoided where possible, because high oxygen levels can become toxic to the body (O’Brien 2013). The general rule is to reduce oxygen delivery to the minimum requirement. Awareness of the patient’s normal lung function is essential when instigating mechanical ventilation, with parameters set to deliver appropriate and realistic targets for arterial blood gas analysis and oxygen saturation (SaO₂). The nurse caring for the patient should be able to recognise unacceptable partial pressure of oxygen (PO₂) levels or partial pressure of carbon dioxide (PCO₂) levels and respond by manipulating the ventilator directly or reporting the inadvertent readings to senior colleagues (Higginson 2011).

**Respiratory rate**
Initial mechanical ventilation rates are typically set at between 12-20 breaths per minute – physiologically normal parameters – however, protective ventilation guidance suggests rates of 20-35 breaths per minute (Kilickaya and Gajic 2013). The set respiratory rate may be increased or decreased to enable elimination or retention of arterial carbon dioxide (CO₂). Increasing the mechanical ventilation delivery rate acts to ‘blow off’ or remove CO₂ from the lungs. This is preferred to increasing volume delivery, which will also facilitate removal of CO₂, but has the potential to cause lung injury (Soni and Williams 2008).

Modern intensive care ventilators have the ability to synchronise the ventilator-delivered breaths with the spontaneous breaths of the patient. If the patient initiates a breath, the ventilator will act to support the breath rather than attempt to override it with one of its own. Ventilators have a variety of settings to deliver either mandatory breaths, synchronised breaths or supported spontaneous patient-initiated breaths. In relation to supported spontaneous patient-initiated breaths, the ventilator has the ability to deliver mandatory ventilation in the event that the patient stops initiating breathing on their own (Open Anesthesia 2018).

**Volume and pressure-controlled ventilation**
Positive pressure can be delivered into the lungs using one of two modes. The ventilator can either be set to deliver a preset tidal volume with each breath (volume-controlled ventilation) or to deliver positive pressure up to a set maximum pressure with each breath (pressure-controlled ventilation) (Courey and Hyzy 2017). Initially, these modes may appear synonymous with one another, because delivering a set tidal volume will generate a pressure, and conversely, generating a pressure will deliver a certain tidal volume. However, in practice, there are different advantages to using each mode in relation to ventilator and lung compliance.

Pressure-controlled ventilation is preferred for most patients in the ICU (Rittayamai et al 2015). In this mode, pressure delivered to the lungs will be set at a constant maximum level, while the actual tidal volume delivered may alter according to the compliance within the lungs. In patients with diseased, infected, obstructed or traumatised lungs, delivering a set pressure will ensure further injury to the lungs can be controlled and limited, whereas delivering a set tidal volume can cause deleterious peaks of pressure,
leading to further lung injury. However, volume-controlled ventilation may be useful in neurosurgical intensive care, because delivering a set ventilator volume enables tighter control of arterial CO₂ levels (Schirmer-Mikalsen et al 2016). This is important when attempting to control raised intracranial pressure, because fluctuations in arterial CO₂ directly affect the vasomotor response of blood vessels in the brain.

**Pressure support**
Pressure support is another form of pressure-controlled ventilation, but this mode is used to support spontaneous breaths made by the patient. Breathing spontaneously through a mechanical ventilator unaided is difficult for the patient, especially when their normal lung mechanics are weakened by lack of muscle use, their underlying illness and the ‘hangover’ effects of sedation (Soni and Williams 2008). This difficulty is compounded by the fact that the ventilator incorporates a series of valves, has long lengths of circuit tubing and culminates at the endotracheal tube, which is a fraction of the size of the patient’s normal airway. Breathing through the ventilator mechanics, tubing and endotracheal tube has been likened to breathing through a long thin straw. Therefore, a degree of positive pressure or high-flow oxygen is required to support spontaneous breathing through a mechanical ventilator and compensate for circuit resistance.

The pressure support mode is used to wean patients off mechanical ventilation. Initially, when patients are waking from sedation and beginning to initiate spontaneous breaths, pressure support will be delivered at a relatively high-pressure level to support their breathing. This can be reduced according to the patient’s requirements until it is deemed appropriate and safe to discontinue and remove them from mechanical ventilation altogether (Hagberg 2017). The aim, in this case, is to synchronise mechanical ventilation support to normal physiological breathing without a ventilator and an endotracheal tube.

**Positive end-expiratory pressure and continuous positive airway pressure**
Normal physiological breathing prevents the lungs from completely collapsing at the end of expiration, since the epiglottis closes the airway, leaving a residual volume of air in the lungs. This is not possible if the larynx is permanently open because of the presence of an endotracheal tube. The term ‘open lung’ is used to refer to the lungs being directly open to the atmosphere by a tube. PEEP ensures that a certain amount of pressure remains in the lungs throughout the entire ventilatory cycle. Usually, the PEEP will be at least 5cmH₂O, increasing depending on the patient’s physiology, for example stiffer lungs may require an increase in PEEP (Kilickaya and Gajic 2013). However, in prolonged ventilation, alveoli may continue to collapse as a result of several physiological and mechanical processes, such as lack of surfactant, sputum retention and endotracheal suctioning. In this case, PEEP should be intermittently increased to higher levels to enable alveoli to re-open. This is known as a lung recruitment manoeuvre.

The non-invasive equivalent of PEEP is continuous positive airway pressure (CPAP). Delivering CPAP requires an inward flow of air against exhalation, which can be uncomfortable for patients (Tobin 2013). Patients tiring on CPAP will require non-invasive pressure support or invasive mechanical ventilation.

**Breath trigger**
When oxygenation and CO₂ removal are critically impaired or require tight control, the patient’s own respiratory trigger (central and peripheral chemoreceptors) can be supressed with the use of anaesthetics. However, when improvement and signs of recovery are evident, sedation will be reduced and the patient will be encouraged to take supported spontaneous breaths through the ventilator. For this to occur, the ventilator needs to sense that the patient is going to take a breath. This function is not required for patients undergoing surgery because the period of mechanical ventilation is usually short and the anaesthetic is usually easily reversed; however, it is a vital component for more sophisticated intensive
care ventilators, where patients will require gradual weaning from mechanical ventilation (Higginson 2011).

The first type of mechanical ventilation trigger was based on pressure sensitivity, in which the ventilator detects a negative pressure at the inspiratory limb of the mechanical ventilator and delivers a pressure-supported breath. One issue with this is that there is an inherent time lag between ventilator sensing and actual support delivery. To combat this, flow triggering is used in preference to pressure sensitivity. All modern ventilators maintain a flow of air and oxygen around the ventilator circuit (flow rate). The ventilator detects this flow via sensors at the inspiratory and expiratory limbs. When the patient attempts a breath, the negative pressure generated enables flow from the ventilator circuit into the lungs. The subsequent deficit in flow is detected by the ventilator and a positive pressure is released to support the breath (Singer and Corbridge 2009). Although this mechanism is more responsive than pressure sensitivity triggering, there remains a miniscule time lag between sensing and delivery. This time lag is sufficient to cause distress for some patients who are on mechanical ventilation.

One innovation in relation to ventilator triggering is neurally adjusted ventilatory assist (NAVA), which is able to sense the electrical activity of the diaphragm before inspiration. As a result, the ventilator is able to synchronise support precisely with each spontaneous, patient-initiated breath and also vary the level of pressure support according to the amplitude of the signal. The alarms will trigger when the set parameters are breached, for example in: apnoeic episodes; high or low inspiratory pressures, respiratory rate or minute volumes; or if a disconnection occurs in the circuit.

Electrocardiogram, SaO$_2$ and end-tidal CO$_2$ monitoring are mandatory for patients who are on mechanical ventilation in hospital. Additionally, patients on prolonged mechanical ventilation will require arterial blood pressure monitoring, arterial blood gas analysis and central venous access. Therefore, nurses have a central role in monitoring, analysing and interpreting a range of inter-related information, and should be able to recognise and action abnormal parameters and identify when the patient requires additional support (Higginson 2011).

**Humidification**

In normal breathing, 75% of respiratory gas conditioning (warming, humidification and cleaning) takes place in the upper respiratory tract (nasopharynx), and the remaining 25% via the trachea (American Association for Respiratory Care et al 2012). However, in patients with an endotracheal tube, these processes are unable to occur. Therefore, it is vital that the gas is clean, warm and humidified when delivering mechanical ventilation invasively or non-invasively.

All mechanical ventilation circuits will contain a respiratory filter to prevent pathogens or foreign material entering the patient’s body, and usually an external warming and humidification system will be added to the ventilator circuit. For prolonged mechanical ventilation, this is achieved by passing the ventilator gas through an external, heated water bath.
While mechanical ventilation technology has improved significantly over the past two decades, it could be suggested that the most significant benefits in relation to mechanical ventilation over this period have resulted from the realisation that it is harmful, and therefore best avoided, or at least limited to the shortest time possible.

Complications
While mechanical ventilation is necessary to provide critically ill patients with potentially life-saving respiratory support, it is not a benign intervention. The common complications of mechanical ventilation relate, in part, to patients being incapacitated with sedatives, analgesics, muscle relaxants and paralytic agents. However, paralytic agents are only warranted in the ICU in extreme situations because of their associated risks, particularly in relation to muscle weakness (Esteban et al 2002).

Incacity can lead to nutrition deficits, muscle weakness, deep vein thrombosis and susceptibility to infection, particularly in the lungs, where an inability to clear secretions and bypassing normal respiratory defence mechanisms – such as the oropharynx and cilia – with an endotracheal tube increases the risk of nosocomial infection (Klompas 2013, Courey and Hyzy 2017).

The presence of an endotracheal tube is associated with the risk of inflammation, infection, vocal cord paralysis, laryngotracheal stenosis and fistula formation, and can be uncomfortable and irritating for patients (Courey and Hyzy 2017). In addition, sedatives and analgesics commonly cause cardiac compromise and induce hypotension, often resulting in the need for vasopressor drug infusion, which is itself potentially noxious and administered via a central venous catheter, increasing the risk of bacteraemia (Band and Gaynes 2015).

Prolonged use of sedatives can also cause delirium when the patient wakes and the cumulative effects of ventilator drug therapy can lead to polyneuropathy, rendering the patient further incapacitated (Jackson et al 2010). The continuous intensive and invasive monitoring required in mechanical ventilation restricts patient mobility and accessibility, and invasive monitoring is associated with additional risks of harm.

Nurses caring for patients on mechanical ventilation can minimise potential harm and complications. Knowledge of adequate sedation practice is essential in achieving the required level of sedation, as assessed using the Richmond Agitation-Sedation Scale (Barr et al 2013). For instance, deep sedation may be required in patients who require paralytic agents, whereas minimal sedation may be required to enable endotracheal tube tolerance while maintaining spontaneous breathing and reaction to stimulation. Effective oral care and endotracheal suctioning technique are also crucial in preventing ventilator-associated pneumonia and trauma to the lung tissue. Regular repositioning and scrupulous pressure area care can also reduce harm to patients on mechanical ventilation (Higginson 2011).

Advances in practice
While mechanical ventilation technology has improved significantly over the past two decades, it could be suggested that the most significant benefits in relation to mechanical ventilation over this period have resulted from the realisation that it is harmful, and therefore best avoided, or at least limited to the shortest time possible. Aside from the risks and complications associated with mechanical ventilation, prolonged use has been shown to directly negatively affect patient morbidity and mortality (Esteban et al 2002, Loss et al 2015).

Mechanical ventilation can cause overdistension of alveoli, which in turn compromises gaseous exchange, leading to alveolar capillary leakage and atelectasis. If unchecked, this injury to the lungs can progress to multiple organ failure. This was demonstrated in a seminal trial by the Acute Respiratory Distress Syndrome
Network et al (2000), which found that mechanical ventilation delivery of larger gas volumes – with subsequent higher pressures – caused greater lung damage than delivery of smaller gas volumes and lower pressures (tidal volumes of 6mL/kg). However, delivery of smaller gas volumes causes retention of CO$_2$ in the circulation, and the only way to mitigate a low volume strategy was to increase the respiratory rate (≤35 breaths per minute). As a result, many ICUs advocated higher levels of CO$_2$ to avoid trauma to the lungs, provided that arterial pH ≥7.2 and SaO$_2$ levels were in the range of 88-95% (Slutsky and Ranieri 2000, PulmCCM 2012). Allowing arterial CO$_2$ to rise as a result is known as permissive hypercapnia, while the onus on preventing direct ventilator-associated harm is known as a ‘protective ventilation strategy’.

Several procedures or adjunts are recommended in cases where standard mechanical ventilation is not achieving correction of respiratory failure. For instance, placing a patient in the prone position has been found to improve the ability to achieve adequate ventilation (Gattinoni et al 2001, Guérin et al 2013). Prone positioning works by using gravity to move fluid or secretions to different areas of the lungs, enabling the expansion of the posterior lung sections and improving gaseous exchange as a result (Guérin et al 2014). Prone positioning requires no additional machinery or costs and has therefore become increasingly popular in ICU practice.

Extracorporeal membrane oxygenation (ECMO) is used to completely rest the lungs and is useful in patients with severe lung injury or disease where standard methods of ventilation are failing (Cho et al 2016). ECMO is achieved via a machine, similar to a haemodialysis circuit. Deoxygenated blood is taken directly from the patient’s circulation via large bore catheters placed in large veins such as the internal jugular or femoral vein, passed through an oxygenating membrane and returned into the patient. As well as increasing blood oxygenation, CO$_2$ is also removed (Rodriguez-Cruz 2017). ECMO is generally used in the ICU when mechanical ventilation fails, and in effect it temporarily isolates the lungs and makes them redundant for ventilation. Following the ‘swine flu’ (H1N1) pandemic, a network of specific ECMO centres was set up in the UK. ECMO technology and equipment is becoming increasingly sophisticated and user-friendly, and it may be that this is readily available in all UK hospitals in the future.

There has also been increased focus on extracorporeal carbon dioxide removal (ECCO$_2$R) as an adjunct to protective ventilation strategies, which involves removing CO$_2$ from the circulation thereby providing partial respiratory support. ECCO$_2$R requires lower blood flow rates than ECMO and is simpler to perform. Partially separating CO$_2$ removal from lung function has several clinical applications. In type II respiratory failure, in which there is an excessive accumulation of CO$_2$, ECCO$_2$R can aid mechanical ventilation. In fact, it has been used pre-emptively to delay or potentially avoid ventilation in patients who are non-sedated and awake. ECCO$_2$R can also potentially be used in conjunction with mechanical ventilation to deliver an ultra-protective lung strategy using small ventilator volumes, without the deleterious side effects of circulatory CO$_2$ accumulation. This is being investigated as part of a UK-wide multicentre trial (McNamee et al 2017).

Improvements in anaesthetic and surgical techniques have meant that many patients previously admitted to the ICU post-operatively are released from mechanical ventilation immediately after surgery. There have also been improvements in the recognition of critically ill patients who may progress to requiring mechanical ventilation, particularly with the introduction of the National Early Warning Scoring (NEWS) system (Royal College of Physicians 2012) and outreach services. It is important these patients are identified early, because delays in mechanical ventilation for those who will ultimately require it can negatively affect their morbidity and mortality (Kang et al 2015). Mechanical ventilation may not always

**KEY POINT**

Several procedures or adjuncts are recommended in cases where standard mechanical ventilation is not achieving correction of respiratory failure. For instance, placing a patient in the prone position has been found to improve the ability to achieve adequate ventilation (Gattinoni et al 2001, Guérin et al 2013).
be an appropriate option, particularly in the absence of a definitive reversible cause of the patient’s underlying breathing difficulties. There are also certain patient groups for whom instigating mechanical ventilation will be futile and should be avoided, for example those who are severely immunocompromised (Wilkinson and Savulescu 2011).

There is a concerted effort in ICUs to limit the deleterious effects of mechanical ventilation. Protocolised sedation, sedation scoring using the Richmond Agitation-Sedation Scale (Barr et al 2013), daily sedation holds and spontaneous breathing trials all attempt to wean patients from mechanical ventilation in a timely manner (Jackson et al 2010). A percutaneous tracheostomy is a valuable adjunct to weaning from mechanical ventilation. A tracheostomy makes the work of breathing easier by reducing dead space in the airway, and is often better tolerated than an endotracheal tube. Therefore, a tracheostomy should enable earlier cessation of sedation and progression of weaning from mechanical ventilation for patients (Lim et al 2015).

Conclusion

Positive pressure ventilation using a mode of pressure control is the most widely used form of mechanical ventilation. Nurses caring for patients on mechanical ventilation require specialist knowledge and skills to monitor, identify and prevent the potential deleterious effects associated with it. While novel interventions such as ECMO, ECCO₂R and NAVA may enable patients to survive mechanical ventilation and aid ventilator weaning, it could be suggested that the most significant development in relation to mechanical ventilation has been the increasing awareness of the potential harm it can cause. This, combined with early recognition of patients who would benefit from mechanical ventilation, alongside strategies to wean patients from mechanical ventilation at the earliest opportunity, should improve patient mortality and morbidity. Therefore, it is important for nurses to have an understanding of the essential components of mechanical ventilation and its associated risks and complications, to enable them to provide safe and effective patient care.

References


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