Clinical application of ventilator modes:
Ventilatory strategies for lung protection

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Summary
Introduction: Identification of the mortality reducing effect of lung protective ventilation using low tidal volumes and pressure limitation is one of the biggest advances in the application of mechanical ventilation. Yet studies continue to demonstrate low adoption of this style of ventilation. Critical care nurses in Australia and New Zealand have a high level of responsibility and autonomy for mechanical ventilation and weaning practices and therefore require in-depth knowledge of ventilator technology, its clinical application and the current evidence for effective ventilation strategies.

Aim: To present an overview of current knowledge and research relating to lung protective ventilation.

Method: A multidatabase literature search using the terms protective ventilation, open lung, high frequency oscillatory ventilation, airway pressure release ventilation, and weaning.

Results: Based on clinical trials and physiological evidence lung protective strategies using low tidal volumes and moderate levels of PEEP have been recommended as strategies to prevent tidal alveolar collapse and overdistension in patients with ALI/ARDS. Evidence now suggests these strategies may also be beneficial in patients with normal lungs.

Lung protective ventilation may be applied with either volume or pressure-controlled ventilation. Pressure-controlled ventilation allows regulation over injurious peak inspiratory pressures; however no study has identified the superiority of pressure-controlled ventilation over low tidal volume strategies using volume-control. Other lung protective ventilation strategies include moderate to high positive-end expiratory pressure, recruitment manoeuvres, high frequency oscillatory ventilation, and airway pressure release ventilation though definitive trials identifying consistently improved patient outcomes are still needed.

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Introduction

Although essential to sustain life, mechanical ventilation is associated with numerous complications that influence patient morbidity and mortality. Research has demonstrated that inappropriate application of invasive mechanical ventilation can damage injured and healthy lungs within 30 min by instigating or perpetuating alveolar and systemic inflammatory response systems.\(^1\)–\(^3\) Lung protective ventilation has been found to reduce mortality in patients with acute lung injury (ALI) and acute respiratory distress syndrome (ARDS).\(^4\)

Identification of the mortality reducing effect of lung protective ventilation using low tidal volumes and pressure limitation is one of the biggest advances in the application of mechanical ventilation.\(^5\) Despite research demonstrating a reduction in mortality,\(^4\) and the development of clinical guidelines to support the use of lung protective strategies, studies demonstrate low adoption of this style of ventilation.\(^6\)–\(^9\) Lung protective ventilation requires clinicians to reconsider traditional ventilator parameters and arterial blood gas goals resulting in slow adoption into routine clinical practice.\(^10\)

To minimise complications, the application of mechanical ventilation must be based on current scientific principles and discontinued at the earliest safe opportunity. Management of mechanical ventilation and its associated processes requires constant surveillance and decision making by a multidisciplinary team including physicians, nurses, and other allied health workers. In Australia and New Zealand critical care nurses have been noted to have a higher level of responsibility and autonomy for mechanical ventilation and weaning practices than nurses in some international settings.\(^11\)–\(^12\) For this reason, it is vital critical care nurses caring for patients receiving mechanical ventilation have appropriate levels of specialist knowledge and skill to manage ventilation and weaning, recognise complications and intervene in a timely manner when ventilator-associated problems arise.\(^13\)

Search strategy

To find relevant articles a multidatabase search that included Medline, EMBASE, Cochrane, and CINAHL was conducted. These four databases were selected to ensure identification of North American (Medline) and European literature (EMBASE), systematic reviews (Cochrane) and literature pertinent to nursing (CINAHL). The search terms 'protective ventilation' and 'open lung' were used individually and in combination. Search limitations included age \(\geq\) 18 years, English language, and publications from 1996 to 2010. A priori, high frequency oscillatory ventilation (HFOV), airway pressure release ventilation (APRV) and weaning were also considered search terms relevant to the aims of this review.

Study selection

Randomised trials evaluating protective lung strategies including HFOV, APRV and weaning strategies were included as well as supporting
literature elucidating the scientific and clinical rationales leading to the conduct of these trials and describing subsequent implementation of findings. Review articles were included that facilitated presentation of a clear and concise description of the application of ventilatory strategies to inform critical care nurses involved in the clinical management of mechanical ventilation and its weaning.

Results

Protective lung ventilation

Historically, recommended ventilation practice routinely suggested tidal volumes of 10–15 mL/kg of predicted body weight, to improve gas exchange. Additionally, positive-end expiratory pressure (PEEP) was used with caution due to its influence on intrathoracic pressure and consequent reduction in venous return and organ perfusion. More recently, this style of ventilation has been found to cause alveolar overdistension and generate cyclic opening and closing of healthy alveoli resulting in ventilator-induced lung injury (VILI). This form of lung injury results in diffuse alveolar damage, increased permeability, pulmonary oedema, cell contraction and cytokine production.

In one of the earliest trials of protective lung ventilation conducted in 53 patients, Amato et al. demonstrated a significant reduction in mortality for ARDS patients with the use of a protective ventilation strategy compared to conventional ventilation. This strategy incorporated low tidal volumes (<6 mL/kg), moderate PEEP levels, inspiratory pressure < 20 cmH₂O above PEEP and permissive hypercapnia. Conventional ventilation was described as tidal volumes of 12 mL/kg and the lowest PEEP to achieve acceptable oxygenation.

Following the publication of this study a number of outcome studies, examining low versus high tidal volume strategies, produced inconclusive results. Subsequently, the ARDSnet group conducted a large, multi-centre, randomised, controlled trial comparing low tidal volume (<6 mL/kg), pressure-targeted ventilation with conventional ventilation defined as tidal volumes of 12 mL/kg. This study was stopped early due to the demonstrated benefit for the group whose ventilation was managed using the low tidal volume strategy. These patients had a significant reduction in mortality compared to the conventional ventilation arm.

Based on the results of this study and physiologic evidence confirming greater numbers of injured cells in lungs ventilated with large tidal volumes and zero end expiratory pressure lung protective strategies using low tidal volumes and moderate levels of PEEP have been recommended as strategies to prevent tidal alveolar collapse and overdistension in patients with ALI/ARDS.

Despite the acceptance of lung protective ventilation for patients with ALI and ARDS, little published data confirms the efficacy of this ventilation strategy for patients without acute lung injury. One study of 332 patients with no evidence of prior lung injury who received conventional tidal volumes (mean 10.9 mL/kg) reported 80 (24%) patients developed lung injury within the first 5 days. A recent randomised, controlled trial comparing tidal volumes of 10 mL/kg versus 6 mL/kg in patients without ALI at the onset of ventilation was stopped prematurely due to increased rates of ALI in the higher tidal volume group. Though further studies are required, clinicians should consider aiming for lower than conventional tidal volumes for all ventilated patients.

Lung protective ventilation may be delivered, either by close monitoring of peak and plateau pressure with a volume-controlled mode, or through the use of pressure-controlled modes. Traditionally, clinicians have favoured volume-controlled modes due to the ability to regulate minute ventilation (VE) and carbon dioxide (CO₂) elimination thus enabling straightforward manipulation of ventilation. Volume-controlled modes do not provide control over peak airway pressures therefore clinicians need to carefully monitor ventilation to avoid injurious pressures. In contrast, pressure-controlled modes allow control over peak inspiratory pressures and inspiratory time. Clinicians are required to monitor minute ventilation and gas exchange due to the lack of guaranteed tidal volume.

Due to the ability to regulate peak inspiratory pressures, pressure-controlled ventilation is increasingly utilised as a protective lung strategy particularly in patients with ALI and ARDS. The variable and decelerating inspiratory flow pattern of pressure-controlled ventilation enables a more rapid alveolar filling and more even gas distribution compared to the constant flow pattern that may be adopted with volume-controlled modes. This inspiratory flow pattern results in improved gas exchange, decreased work of breathing and prevention of overdistension in healthy alveoli. During pressure-controlled ventilation set inspiratory pressure is achieved at the beginning of the inspiratory cycle and maintained for the set inspiratory time. This promotes recruitment of alveoli with high opening pressures and long time con-
Clinical studies have identified improved oxygenation, lower peak inspiratory pressures, higher mean airway pressures, and reduced duration of ventilation when comparing pressure-controlled modes to conventional volume-controlled ventilation. Studies comparing the use of pressure-controlled ventilation to a low tidal volume strategy applied using a volume-controlled mode have failed to identify a reduction in mortality for ARDS patients, suggesting the benefits of pressure-controlled ventilation may be more about the ability to consistently limit tidal volume than improved oxygenation as the result of increased mean airway pressure.

**Open-lung strategies**

Pressure-targeted, low tidal volume strategies may not be sufficient to limit lung injury. Animal studies have shown lung injury is also caused by the use of zero or low PEEP resulting in cyclic opening and closing of alveoli. These studies also demonstrated further lung damage could be prevented if PEEP was set at a level to keep the lung open. PEEP may be beneficial only if the lung has sufficient potential for recruitment which can only occur in collapsed as opposed to consolidated lung.

The setting of optimal PEEP remains controversial. Low PEEP levels have been shown to be independently associated with higher mortality for ARDS patients in a number of studies. Two recently published randomised, controlled trials comparing low tidal volume ventilation and conventional PEEP to low tidal volume ventilation and high PEEP with and without additional recruitment manoeuvres (40 cmH2O applied for 40 s) report no difference in hospital or 28-day mortality. Both studies did, however, demonstrate improvements in other patient outcomes including a lower incidence of refractory hypoxemia and reduced use of rescue therapies such as nitric oxide, prone positioning, high frequency oscillatory ventilation and extracorporeal membrane oxygenation for the Canadian investigator-led study and improved lung function and reduction of the number of ventilation and organ-failure free days in the study conducted in France.

Arguably PEEP levels used in these two studies were not sufficiently high to maintain the lung open (mean PEEP 15.6 and 14.6 cmH2O, respectively). Barbas et al suggest PEEP as high as 18–26 cmH2O is required to maintain the lung open and therefore optimise oxygenation. Animal models have shown PEEP of 16 cmH2O was needed to open the lung, with alveolar collapse occurring at 14 cmH2O. Few clinicians currently routinely use PEEP at these settings.

**Combining protective lung ventilation and spontaneous breathing (partial ventilatory modes)**

Airway pressure release ventilation (APRV) and biphasic positive airway pressure (BiPAP) are two modes of mechanical ventilation that allow unrestricted spontaneous breathing during the inspiratory and expiratory time cycles, using an active expiratory valve. Both modes are pressure limited and time cycled. Ventilation occurs via the time cycled switching between two set pressure levels. In the absence of spontaneous breathing, these modes resemble conventional pressure limited, time-cycled ventilation.

Spontaneous breathing during ventilation reduces the negative cardiovascular effects of mechanical ventilation by improving venous return, and ventricular filling resulting in increased cardiac output, oxygen delivery and organ perfusion. Further, spontaneous breathing reduces the need for sedation and muscle relaxants resulting in reduced durations of ventilation and ICU stay and ventilator-associated complications.

A proposed advantage of APRV and BIPAP, compared to conventional pressure-controlled ventilation, is the improved distribution of gas to dependent lung regions. This occurs as the result of spontaneous breathing enabled during both the inspiratory and expiratory time cycles. In the absence of pressure support, spontaneous breathing achieved with APRV and BIPAP resembles a sinusoidal pattern. Radiologic studies indicate this breathing pattern directs gas to dependent well-perfused regions of the lungs promoting alveolar recruitment and preventing atelectasis due to the movement of posterior muscular sections of the diaphragm. The net result of this pattern of gas distribution is improved ventilation-perfusion matching.

Within the scientific literature descriptions of APRV and BIPAP lack clarity. The two modes are described by various authors as distinct modes, a continuum of ventilator styles, or as synonymous. A systematic review of studies describing APRV and BIPAP found the major distinction between the
two modes was the mean duration of set expiratory time; nearly three times longer in BIPAP studies compared to reports of APRV. The application of APRV was more frequently described as a prolonged inspiratory time and shortened expiratory time resulting in an extreme inverse ratio. In contrast, no BIPAP studies described this type of ventilatory settings.

Due to concerns for ventilator branding, various other acronyms for modes with similar features include BiLevel™ (Puritan Bennett, Pleasanton, CA, GE Healthcare, Madison, WI) Bivent (Maquet, Solna, Sweden), DuoPaPTM (Hamilton Medical, Rhäzüns, Switzerland), PCV™ (Dräger Medical, Lübeck, Germany) or BiPhasic™ (Viasys, Conshocken, PA). Frequently clinicians are exposed to a number of different ventilator brands and models during their clinical practice. The use of different acronyms for essentially the same mode of mechanical ventilation may result in uncertainty for clinicians involved in the selection and titration of these modes.

Recruitment manoeuvres refer to application of super high PEEP levels (30–40cmH2O) for sustained periods (20–40s) to ‘recruit’ slow opening alveoli with the intention of improving ventilation/perfusion matching and therefore oxygenation. Effective recruitment may be difficult to assess with the potential for either overdistension of alveoli or failure to recruit. Moreover, once the recruitment manoeuvre is terminated, derecruitment may occur rapidly. Recruitment manoeuvres in humans have not produced consistent results in clinical studies. Furthermore the best method in terms of pressure, duration and frequency have yet to be confirmed.

APRV applied with a prolonged inspiratory time offers an alternative approach to open-lung ventilation by providing a near continuous recruitment manoeuvre. Sustained application of high levels of continuous positive airway pressure (CPAP) is combined with brief releases in pressure to enable alveolar ventilation and CO2 removal. Opening pressure is maintained for a prolonged period \(T_{\text{high}}\) promoting recruitment of slow opening alveoli. This enables unstable lung units time to fill and equilibration of volume as the result of collateral ventilation. The short release permits only partial emptying of lung volume and prevents unstable alveoli from collapsing.

In the original description of APRV, the \(T_{\text{high}}\) and \(T_{\text{low}}\) were 1.8 and 1.3s respectively indicating a moderate inverse ratio. More recently, Habashi described a technique that utilised a \(T_{\text{high}}\) extended by 4–6s to improve recruitment by increasing the mean airway pressure. The \(T_{\text{low}}\) may be reduced to as little as 0.2s (default setting of 0.8s) in order to terminate the expiratory flow early causing retention of lung volume thus preventing derecruitment.

This style of APRV differs conceptually from conventional modes of ventilation. In order to achieve tidal ventilation, conventional modes elevate airway pressures from a low baseline pressure, whereas APRV, uses a short deflation to a lower pressure level then returns to a high baseline pressure. The release phase of APRV reduces the risk of overdistension associated with conventional ventilation.

APRV has been shown to be an effective mode in the management of recruitable diseases such as ALI and ARDS, which are characterized by atelectasis and ventilation/perfusion mismatch. However, a recent study using computer tomography assessment of lung aeration failed to demonstrate a difference in lung consolidation when comparing APRV to pressure-controlled synchronised intermittent mandatory ventilation (SIMV-PC) with pressure support. Based on the lack of large clinical trials, an evidence-based review of mechanical ventilation in sepsis-induced ALI and ARDS recommended APRV should only be used in controlled clinical trials or as a rescue therapy.

High frequency oscillatory ventilation

Recently, interest has been rekindled in high frequency oscillatory ventilation (HFOV) as a lung protective ventilation strategy in adults. Alveolar overdistension is limited through the use of sub-dead-space tidal volumes. Cyclic collapse of alveoli is also prevented by maintaining a high end expiratory lung pressure. High frequency (between 3 and 15 Hz) oscillations create pressure waves enabling CO2 elimination. Oxygenation is facilitated through application of a constant mean airway pressure via the bias flow (rate of fresh gas).

Delivery of HFOV requires a specialised ventilator and requires manipulation of four variables: mean airway pressure (cmH2O), frequency (Hz), inspiratory time, and amplitude (or power \[\delta P\]). In adults, recommendations for the initiation of HFOV state mean airway pressure should be set 5cmH2O above the peak airway pressure achieved with conventional ventilation. The recommended frequency range is 3–10 Hz with 5Hz conventionally used to initiate HFOV. Inspiratory time is set at 33% and the amplitude setting is determined by adequate CO2 elimination. Increased CO2 elimination is achieved by lowering the frequency and increasing the amplitude. A published roundtable
discussion recommended using the maximum amplitude setting combined with the highest tolerated frequency to optimise the potential lung protective effects of HFOV. Volume-recruitment manoeuvres are required in HFOV to reverse atelectasis caused by less than dead-space tidal volumes. Recruitment manoeuvres consist of application of high mean airway pressures (40 cmH₂O) for 30–40 s.

Animal studies have shown that HFOV is associated with reduced levels of inflammatory mediators compared to conventional ventilation. While early human studies identified improved oxygenation and safety associated with this mode, currently there is limited evidence to evaluate HFOV in terms of its effect on mortality and ventilator-free days. Several case series and a small number of randomised studies have demonstrated HFOV to be safe and effective for improving oxygenation of adult patients with ARDS. These studies also demonstrate a potential for improved survival for a subgroup of patients transitioned early to HFOV. Recently, sustained improvements in oxygenation have been found for patients with early-onset ARDS leading to the conduct of a large clinical trial to evaluate mortality benefits of this ventilation strategy.

Weaning

No ventilation strategy can be more lung protective than the timely discontinuation of mechanical ventilation. Evidence-based consensus guidelines published for weaning in 2001 and 2007 emphasise the importance of preventing unnecessary delays in the weaning process, early recognition of a patient’s ability for spontaneous breathing, and the use of a systematic method to identify the potential for extubation. Failure to do so may unnecessarily increase the duration of mechanical ventilation and place patients at risk of additional complications such as ventilator-associated pneumonia, VILI, airway trauma, discomfort, delirium and agitation associated with prolonged sedation and neuromuscular blockade, inadvertent extubation, and endotracheal tube obstruction.

Despite the above recommendations, evidence suggests decisions to commence weaning and attempt extubation continue to be delayed. Critical care nurses need to be able to recognise patients capable of spontaneous breathing and transition these patients to spontaneous ventilator modes and extubation while monitoring for signs of respiratory distress.

Implementation of various organisational strategies such as weaning teams and non-physician-led weaning protocols may assist in the timely recognition of weaning and extubation readiness. Recently, coupling of a sedation and weaning protocol was found to result in a 3-day reduction in the duration of ventilation compared to standard care in four North American hospitals. The effect of weaning protocols may vary according to the organisational characteristics of the intensive care unit (ICU). Some studies reporting the introduction of a weaning protocol have failed to identify a reduction in the duration of ventilation. This lack of effect is attributed to organisational structures such as an intensivist-led ICU model, high levels of physician staffing, structured ward rounds, collaborative discussion and more frequent medical review. These organisational characteristics are reported for ICUs in Australia and New Zealand.

Automated computerised systems have been proposed as a means of enabling more efficient weaning by providing improved adaptation of ventilatory support through continuous monitoring and real-time intervention. One such system, SmartCare/PS, monitors the three respiratory parameters, frequency, tidal volume, and end-tidal carbon dioxide (etCO₂) concentration, every 2 or 5 min and periodically adapts pressure support (PS). Based on these three parameters, SmartCare/PS establishes a respiratory status diagnosis and may either decrease or increase PS, or leave it unchanged to maintain the patient in a defined “respiratory zone of comfort”. Once SmartCare/PS has successfully minimised the level of PS, a 1-h observation period occurs. For patients who remain within the respiratory zone of comfort throughout the observation period, SmartCare/PS recommends to “consider separation” indicating the patient’s respiratory status now suggests the patient will tolerate extubation.

SmartCare/PS has been found to substantially reduce the duration of ventilation and ICU length of stay when compared to physician-controlled weaning using local guidelines in five European ICUs. Substantial reductions in weaning duration were not confirmed when the SmartCare/PS system was compared to weaning managed by experienced critical care specialty nurses, using a 1:1 nurse-to-patient ratio in a single Australian ICU.

Conclusion

It is now widely accepted that inappropriate ventilatory management may induce or worsen lung injury. Despite the large amount of research that has generated and confirmed this conclu-
Clinical application of lung protective ventilation

sion, lung protective ventilatory strategies are not consistently applied and weaning and extubation continue to be delayed. Critical care nurses need to establish a strong knowledge base of current research and evidence-based guidelines to promote effective and appropriate management of patients requiring mechanical ventilation. Of particular relevance for critical care nurses are collaborative decision making models and appropriate education that foster the knowledge and skills to facilitate timely recognition of a patient’s readiness for weaning and subsequent extubation.

Conflict of interest statement

The author has no potentially conflicting financial interests to be declared.

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Clinical application of lung protective ventilation


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