Optimizing Mechanical Ventilation During General Anesthesia

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Optimal mechanical ventilatory support is a vital component of intraoperative anesthesia care, lung protection, and minimizing postoperative pulmonary sequela. Although concepts surrounding ventilation can be multifaceted and ambiguous, a pragmatic approach coupled with contemporary evidence and skilled assessments will facilitate ideal intraoperative management. Effective mechanical ventilation is dependent on obtaining the best pulmonary mechanics, including compliance, resistance, and gas exchange. Optimally titrated positive end-expiratory pressure is the foundation for ideal pulmonary mechanics, preventing ventilator-induced lung injury, and minimizing postoperative pulmonary complications. A knowledgeable application of pressure support ventilation can offer additional advantages during general anesthesia and emergence, providing synchronized ventilation and augmenting the patient’s own respiratory efforts. These concepts, coupled with clinical expertise, will offer insight into the methods, tools, and techniques available to modern anesthetists.

Keywords: Positive end-expiratory pressure, pressure support ventilation, pulmonary mechanics, ventilator-induced lung injury.

Introduction
The ever-evolving nature of medicine and science requires healthcare practitioners to periodically reconsider our understanding of clinical concepts. Today, there is substantial evidence advocating lung protective techniques be used in patients with normal lung function.1-5

In a 2006 multicenter study of tidal volume (Vt) during anesthesia, Jaber et al6 noted that more than 80% of operating room patients were ventilated with no positive end-expiratory pressure (PEEP) and nonprotective settings. Similar findings were noted in a study of intensive care patients receiving protective ventilation and requiring surgery. Protective settings were continued intraoperatively in only 53% of patients.7 Mechanical ventilation poses a known risk of injury and complications, with postoperative pulmonary sequela substantially contributing to mortality and morbidity.4,8,9

Contemporary anesthesia ventilators span a spectrum of capabilities. Irrelevant to variations in modes and models, a foundational understanding of pulmonary mechanics and physiology will allow confident and objective management in response to the dynamic needs of the patient. A knowledge of ventilator capabilities and response to patients is essential. At its core, mechanical ventilation should mimic natural breathing patterns. Bearing in mind the patient’s own respiratory pattern, it is easy to see how settings can be nonphysiologic, altering ventilation and perfusion (V/Q) relationships. Humans...
possess natural variability in breathing, sighing several times per hour to maintain recruitment and satisfy pulmonary stretch receptors. Respiratory patterns adapt in response to Pa\textsubscript{CO\textsubscript{2}}, Pa\textsubscript{O\textsubscript{2}}, pH, and baroreceptive signals. The more ventilatory parameters set by providers, the more likely respirations will run contrary to physiologic signals and lead to dyssynchrony.

Pulmonary Mechanics

An understanding of pulmonary mechanics is vital to patient assessment during mechanical ventilation. Pulmonary mechanics include factors such as flow, volume, pressure, compliance, and resistance. These factors directly affect lung volumes and therefore functional residual capacity (FRC) and gas exchange. Goals during mechanical ventilation include optimizing the patient’s pulmonary physiology, providing effective gas exchange, maintaining alveolar recruitment, reducing injury potential, and ensuring hemodynamic stability. Analyzing and incorporating measurements of pulmonary mechanics during your assessment will provide the information required for optimal intraoperative mechanical ventilation.

Improper intraoperative ventilation may create overdistention, allow end-expiratory alveolar collapse, or induce lung injury. Compliance measurements are a key to ventilator management in patients with and without lung disease. Respiratory system static compliance (Crs) is the pressure burden exerted on the lung for any volume change. It is calculated as change in volume over the change in pressure (Table 1) as follows: 

\[
\text{Crs} = \frac{\Delta V}{\Delta P} = \frac{V_T}{\text{Plateau Pressure} - \text{PEEP}} \text{ in mL/cm H}_2\text{O}
\]

\[
\text{Crs} = \frac{450}{15 - 5} = \frac{450}{10} = 45 \text{ mL/cm H}_2\text{O}
\]

Dynamic compliance (DyCrs) is similar; however, it incorporates airway resistance (Raw) within the calculated value (Table 1).

\[
\text{DyCrs} = \frac{V_T}{\text{PIP} - \text{PEEP}} \text{ in mL/cm H}_2\text{O}
\]

\[
\text{DyCrs} = \frac{450}{17 - 5} = \frac{450}{12} = 37.5 \text{ mL/cm H}_2\text{O}
\]

Airway resistance (Raw) is calculated as pressure per unit of flow, per unit of time: 

\[
\text{Raw} = \frac{\Delta P}{\text{Flow}} \text{ in cm H}_2\text{O/L/s}
\]

\[
\text{Raw} = \frac{17 - 15}{1} = 2 \text{ cm H}_2\text{O/L/s}
\]

Physiologic dead space (V\text{DS}/V\text{T}) is measured as 

\[
\text{V}_{\text{DS}}/V_T = (\text{PaCO}_2 - \text{PeCO}_2)/\text{PaCO}_2
\]

\[
\text{V}_{\text{DS}}/V_T = 49 - 41/49 = 8/49 = 16\%
\]

Time constant (TC) is calculated as 

\[
\text{TC} = \text{Raw} \times \text{Crs}
\]

\[
\text{TC} = 0.045 \text{ L/cm H}_2\text{O} \times 2 \text{ cm H}_2\text{O/L/s} = 0.09 \text{ s}
\]

Table 1. Pulmonary Mechanics: Equations and Examples

<table>
<thead>
<tr>
<th>Mechanics</th>
<th>Equation</th>
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<tr>
<td>Static compliance (Crs)</td>
<td>(\text{Crs} = \frac{V_T}{\text{PIP} - \text{PEEP}} \text{ in mL/cm H}_2\text{O})</td>
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Corresponding with clinical assessment, measurements of Raw give objective data to consider during mechanical ventilation or in diagnosing airway compromise. Raw coincides with pulmonary time constants, a product of Raw and Crs, which demonstrates variability among lung units. Airway and lung units are rarely homogeneous, particularly in patients with underlying lung disease. Raw is divided between artificial and natural airways. Artificial airways have a fixed resistance, whereas natural airways are dynamic, responding to neuroendocrine and physiologic changes.

Raw is calculated as pressure per unit of flow, per unit of time: 

\[
\text{Raw} = \frac{\text{PIP} - \text{Pplat} \text{Flow}}{\text{in SUV min or 1 L/s}}
\]

An inspiratory flow of 60 L/min or 1 L/s would produce a Raw as follows (Table 1): 

\[
17 - 15 = 2 \text{ cm H}_2\text{O/L/s}
\]

Thus, inspiratory Raw is 2 cm H\textsubscript{2}O/L/s with optimal Raw measuring less than 10 cm H\textsubscript{2}O/L/s.
The PIP-Pplat differential can offer a surrogate indicator of inspiratory Raw during rapid assessment. Raw cannot be determined when using variable flow modes such as pressure control ventilation (PCV). Indeed, one indication for PCV is to overcome variable time constants and high Raw areas. Its descending flow pattern coupled with a fixed inspiratory time and pressure improve the distribution of ventilation and gas exchange.

Expiratory resistance is typically higher than inspiratory and more applicable for the care of patients with obstructive lung disease. It can be evaluated using waveforms and peak expiratory flow rates as a convenient single numerical indicator, thereby enhancing your assessment. Flow/time, volume/time, and pressure/time
Positive End-Expiratory Pressure Optimization and Trials

The concept of PEEP was described as early as 1938. Unfortunately, optimal use and application elude many modern practitioners. The foundational setting in mechanical ventilation, PEEP should be individually set for each patient. All other parameters and settings rely on appropriate levels of PEEP to ensure adequate ventilation, FRC, and recruitment. General anesthesia creates major changes in pulmonary physiology, including alveolar collapse, absorption and compression atelectasis, a loss of respiratory muscle tone, FRC, and closing capacity. These alterations in pulmonary physiology may last for several days, resulting in postoperative pulmonary complications and other sequelae.

Providing PEEP levels sufficient to maintain alveolar recruitment is instrumental in protective ventilation. Therefore, what is optimal PEEP, and how is it determined? This must be individually determined for each patient. The distribution of ventilation changes with positive pressure ventilation (PPV) secondary to pulmonary heterogeneity, even in healthy patients. Ventilation is directed to low resistant areas while high resistant, low compliant areas receive inadequate gas exchange. Levels of PEEP may be insufficient to maintain recruitment in certain areas while others experience overdistention, risking VILI.

Several indexes and physiologic factors require consideration when one is evaluating optimal PEEP or performing PEEP trials. In addition to pulmonary mechanics and gas exchange, consideration is required for hemodynamics, underlying pulmonary disease, surgical procedure, and positioning. Basic PEEP trial methods involve monitoring compliance and/or its surrogates (PIP, Pplat) with progressive changes in PEEP. During PEEP trials DyCrs has proved to be a particularly valuable indicator, accounting for changes in Raw in addition to Crs. Alveolar to arterial gradient, oxygenation, and VDS/Vt will generally improve in conjunction with compliance and resistance, indicating optimal settings. Suter et al. discovered that the best Crs coincided with maximum oxygen transport and the lowest VDS/Vt. Maisch et al. found that a combination of best compliance and lowest VDS/Vt in healthy anesthetized patients to be superior to other methods of optimization, both of which are easily employed intraoperatively. Results of several intraoperative studies concluded that moderate PEEP levels averaging approximately 10 cm H2O were ideal in decreasing atelectasis, improving FRC, and providing the best gas exchange. The best Crs, DyCrs, Raw, VDS/Vt, and oxygenation are key indicators in demonstrating optimal settings that deliver dividends to patients both intraoperatively and postoperatively (Table 2).

A real-world example may help demonstrate these theories, realizing that a steady state is necessary, avoiding changes in position or other conditions that would alter pulmonary mechanics. Consider a patient receiving volume-controlled ventilation. After alveolar recruitment maneuvers, the anesthesia provider can increase PEEP while monitoring PIP/Pplat. This is often done in increments of 2 cm H2O (ie, from 6 to 8 cm H2O). If PIP/Pplat measurements fall, remain the same, or increase less than the change in PEEP, alveolar recruitment is occurring with an increasing FRC. If the initial PIP was 20 cm H2O and if following an increase in PEEP of 2 cm H2O for 15 minutes, the PIP falls to 19 cm H2O, the FRC is improving with alveolar recruitment. Coinciding improvements
in DyCrs, Crs, oxygenation, and \( V_{D}V_{T} \) would also be expected over a 10- to 20-minute trial period. The process may be repeated until the best Crs, DyCrs, \( V_{D}V_{T} \), and oxygenation are achieved, indicating optimal settings. Conversely, an increase in PIP/Pplat greater than the change in PEEP would indicate a drop in compliance, overdistention, and increased risk of VILI. After confirming that the higher pressures do not stem from outside causes, returning the PEEP to its previous level would be indicated, with consideration for lower adjustments to achieve optimal Crs or DyCrs. For patients being ventilated with PCV, the anesthesia provider may use a similar extrapolation in DyCrs or Crs, noting changes in the delivered \( V_{T} \) for a set PIP and/or \( \Delta P \). Pressure is fixed; therefore, \( V_{T} \) changes are indicative of changes in compliance, recruitment, and FRC in contrast to PIP/ Pplat changes during volume ventilation.

Included in any discussion regarding PEEP is the concern over hemodynamic effects. Positive pressure ventilation alters hemodynamics via 3 main mechanisms: diminished venous return, diminished right ventricular output secondary to increased pulmonary vascular resistance, and reduced left ventricular preload. Hypovolemic conditions compound these effects, particularly in patients without lung disease. Pulmonary vascular resistance may be increased when alveolar capillary beds are compressed, promoting increased \( V_{D}V_{T} \) and hypoxemia. Hypoxic pulmonary vasoconstriction in atelectatic, under recruited regions exacerbate the increased pulmonary vascular resistance. These effects are decreased or offset with appropriate PEEP and alveolar recruitment.

The goals of PEEP include decreasing VILI as well as improving gas exchange and oxygen delivery to the tissues. Therefore, optimal PEEP promotes these goals without compromising hemodynamics; otherwise, oxygen delivery would be curtailed. These facts underscore the importance of achieving optimal, individual PEEP for each patient. Neither continuous cardiac output nor hemodynamic measurements are available for most patients. Therefore, we must rely on pragmatic indicators of optimal PEEP. Suter et al. found the best Crs to be the strongest indicator for optimal PEEP, oxygen delivery, and thus optimal cardiopulmonary function. This conclusion was confirmed in several other studies. When hemodynamic effects are noted, a thorough assessment to ascertain cause and idea settings should be completed, including best treatment for resolution.

Positive end-expiratory pressure is instrumental in preventing postoperative pulmonary complications. Pulmonary complications occur in 5% to 10% of patients undergoing nonthoracic surgery and in 22% of thoracic surgeries or high-risk patients. Atelectasis impedes surfactant production, catalyzing a vicious cycle that can persist for weeks after surgery and can lead to other sequelae. Pneumonia or bronchitis, hypoxemia, bronchospasm, acute lung injury, exacerbation of existing lung disease, and pulmonary emboli are all possibilities. Retained secretions act as a nidus for infectious organisms, leading to pneumonia with hypoxemia, fever, and leukocytosis. Pulmonary complications are second only to cardiovascular events in degree of severity. The one all-encompassing characteristic of pulmonary complications is that all are modifiable, and most are preventable.

### Pressure Support Ventilation

Since the advent of mechanical ventilation, medicine has struggled to create a ventilatory mode that could mimic a patient’s own physiologic patterns. Pressure support ventilation was developed in the early 1980s with microprocessor-based ventilators that were sensitive to a patient’s effort. Classified as a spontaneous mode, PSV only partially assists the patient and serves as one of the hallmark modes for weaning patients and promoting ventilator/patient synchrony. Despite a few shortcomings, PSV can be applied as a primary mode for patients under general anesthesia who are breathing spontaneously. One drawback includes the lack of a minimal \( V_{T} \) or minute ventilation setting with no automated backup for periods of apnea. Hybrid modes such as PSV-Protect were developed to allow a minimal minute ventilation to be set and maintained.
Pressure support ventilation has demonstrated effectiveness in all artificial airways, including endotracheal (ET) tubes and laryngeal mask airways (LMAs). Given an adequate fitting mask, PSV with PEEP can mimic noninvasive bilevel positive airway pressure (BiPAP). Pressure support has been effective at reducing the work of breathing associated with endotracheal intubation and mechanical ventilation. Consider the Poiseuille law concerning flow through a tube or cylinder. The law demonstrates that flow is directly proportional to the radius of the tube and the pressure differential, proximal to distal. Smaller ET tubes are associated with significantly higher resistance and work of breathing indexes. Pressure support delivers a driving pressure to the proximal airway, overcoming Raw and augmenting inspiratory flow across the length of the ET tube. Two studies with a limited number of patients yielded evidence suggestive of upper airway edema after extubation, contributing to an increased work of breathing equivalent to intubation, limiting the need for PSV. Notwithstanding this hypothesis, providing adequate support, minimizing the work of breathing, augmenting pulmonary physiology, and optimizing patient comfort provide substantial benefit both intraoperatively and postoperatively.

Whenever modes like volume-controlled ventilation or PCV are employed, clinicians program most of the settings, including frequency, \( V_T \), inspiratory flow, and inspiratory time. In using PSV, the provider only sets the pressure support level above PEEP and adjusted to deliver normal spontaneous \( V_T \) averaging 4 to 5 mL/kg IBW. Support levels from 3 to 10 cm H\(_2\)O are commonplace. It is important to consider patient factors, including muscle strength, pulmonary pathology, comfort, surgical procedure, and work of breathing. Providers routinely err by setting PSV levels too high rather than too low. Inappropriately elevated pressure support levels are associated with ineffective efforts, periodic breathing, apnea, and dyssynchrony. These findings are often identified during emergence when PSV levels are set inappropriately high.

Pressure support is delivered to the proximal airway after sensing the patient’s inspiratory effort, providing the necessary flow and volume for the inspiratory time required by the patient. Sensitivity measures a differential change in circuit flow, traditionally 2 to 3 L/min, which is very responsive to patient efforts. Autotriggering has been reported with cardiac oscillations and chest wall rebound, which can be corrected with sensitivity adjustments and titration. Increasing the flow differential to 4 to 5 L/min will decrease responsiveness and eliminate any oversensitivity. Observing the patient’s respiratory pattern, circuit pressures, waveforms, and ETCO\(_2\) can confirm spontaneous efforts and synchrony, thus ensuring that sensitivity is set appropriately to prevent autotriggering yet responsive to patient efforts. Inspiratory flow progresses in a characteristic decelerating pattern (Figure 2). As the patient’s inspiratory needs are met, flow progressively declines until it reaches a predeter-
mined level, usually 25% of the peak inspiratory flow, at which time the breath is terminated. Pressure support ventilation allows the patient to control their own respiratory pattern, including inspiratory flow, inspiratory time, V_T, respiratory rate, and pattern. Variability in respiratory patterns is essential with as little as 30% beneficial at improving V/Q relationships, particularly in patients with lung disease.\(^{11,36}\) Because of these characteristics, PSV is considered one of the most comfortable and physiologic modes in mechanical ventilation.

Pressure support ventilation allows for the preservation of several physiologic functions that are beneficial to patients under general anesthesia. A balance between the negative effects of PPV and the advantages of spontaneous respirations can be appreciated with PSV. Active inspiratory efforts promote improved distribution of ventilation, augmented venous return, V/Q matching, and several other benefits seen in spontaneous respiratory physiology. A 2012 randomized controlled trial found that PSV prevented ventral redistribution of ventilation compared with PCV.\(^{37}\) Similarly, PSV was found to improve minute ventilation and gas exchange while preserving hemodynamic function during inhaled anesthesia.\(^{32}\) In 2013, Capdevila et al\(^{38}\) compared patients undergoing knee arthroscopy, using LMAs, and randomly assigned patients to controlled mandatory ventilation, spontaneous breathing, or PSV. Patients receiving PSV experienced the lowest propofol and fentanyl requirements, decreased emergence times, and fastest LMA removal times compared with controlled mandatory ventilation and spontaneous breathing, with no untoward side effects.\(^{38}\) Another randomized controlled trial of 34 pediatric patients undergoing adenotonsillectomy found lower intraoperative sevoflurane requirements, lower anesthesia times, decreased extubation times, and lower pain scores in the postanesthesia care unit in patients ventilated with pressure support vs spontaneous ventilation.\(^{39}\) Furthermore, intraoperative use of PSV in moderately obese patients has demonstrated improved perioperative lung function, oxygenation, an improved distribution of ventilation to the dorsal regions of the lung, and positive effects that persisted into the postoperative period.\(^{40}\)

Pressure support ventilation has numerous promising characteristics that skilled clinicians may employ; however, as with any tool, it must be used appropriately. Anesthetic and opioid levels can be titrated in patients breathing spontaneously with appropriate levels of pressure support. Pressure support ventilation may be used in overcoming the depressive effects of anesthetics and muscle relaxants, providing support during emergence, augmenting V/Q matching and gas exchange, preventing atelectasis, eliminating potent inhalational agents, and providing a synchronized mode of ventilation. Assessment of muscle strength and the effectiveness of respirations on PSV can be confounding, however, proving to be a barrier to its use during emergence. Support levels set inappropriately potentially mask muscle weakness, create respiratory alkalosis, alter neuroreflexive controls of respiration, produce periodic irregular respirations, and lead to dysynchrony. In setting pressure support, few factors require consideration outside achieving a V_T approximately 4 to 5 mL/kg IBW, which may be accomplished with levels between 3 and 6 cm H_2O. Other patients may require little to no pressure support, indicative of recovery. The required level of support may be used as an indicator akin to spontaneous respirations with an open adjustable pressure-limiting valve. Patients with residual anesthesia or persistent muscle weakness may require higher PSV levels. Work of breathing, respiratory rate, pattern, and effort are all assessed. Body habitus, comorbidities, position, and surgical procedure are also considered in support requirements. When patient parameters are favorable and extubation is imminent, PEEP and pressure support levels can remain intact up to extubation.

**Conclusion**

Management of mechanical ventilation, like anesthesia, is an art supported by science. Contemporary theories and practices have evolved to ensure efficiency and prevent iatrogenic injury, learning from the mistakes of our past. Advances in computer microprocessor and other technology offer high-bred modes and functions that meet the needs of an array of patients. In applying concepts of pulmonary physiology and mechanics, anesthetists possess the ability to tailor ventilator settings according to the patient’s physiologic requirements. Optimally applied PEEP can ensure a patient’s cardiopulmonary homeostasis while preventing VILI and postoperative sequelae. Additionally, PSV employed effectively offers anesthetists a spontaneous mode with clear physiologic advantages.

**REFERENCES**

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DISCLOSURES
The authors have declared no financial relationships with any commercial entity related to the content of this article. The authors did not discuss off-label use within the article. Disclosure statements are available for viewing upon request.