Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Intraoperative Ventilator Management of the Critically Ill Patient

Erin Hennessey, MD, MEHP[a,*], Edward Bittner, MD, PhD, MSEd, FCCM[b], Peggy White, MD[c], Alan Kovar, MD[d], Lucas Meuchel, MD[e]

KEYWORDS

- Intraoperative lung-protective ventilation • Ventilator-induced lung injury
- Respiratory mechanics • Postoperative pulmonary complications
- Critically ill patients • Operating room

KEY POINTS

- Although low tidal volume and reduced airway pressures are standard components of lung-protective ventilation, further individualization of ventilation may be necessary based on patient characteristics and surgical conditions.
- Noninvasive tools that provide real-time, continuous, dynamic lung imaging (lung ultrasound, electrical impedance tomography) or pressure measurements (esophageal manometry) may help to better identify different lung morphology including lung overdistension and atelectatic components as well as response to specific interventions.
- Using predictive risk scores to identify patients at risk for postoperative pulmonary complications in addition to recognition of specific patient populations (those with obesity, sepsis, or acute respiratory distress syndrome) or surgical procedures (laparoscopic, abdominal, or one-lung ventilation needs) that are at risk can help physicians implement ventilator management plans in the operating room to those that may benefit from lung-protective strategies.

INTRODUCTION

More than 2 decades ago, we learned that low tidal volumes (TVs; 6 mL/kg predicted body weight [PBW]) and lower plateau pressures ($\leq$30 cmH_2O) resulted in reduced patient mortality for patients suffering from acute respiratory distress syndrome (ARDS).[1]

[a] Stanford University - School of Medicine Department of Anesthesiology, Perioperative and Pain Medicine, 300 Pasteur Drive, Room H3580, Stanford, CA 94305, USA; [b] Department of Anesthesia, Critical Care and Pain Medicine, Harvard Medical School, Massachusetts General Hospital, Boston, MA 02114, USA; [c] University of Florida College of Medicine, Department of Anesthesiology, 1500 SW Archer Road, PO Box 100254, Gainesville, FL 32610, USA; [d] Oregon Health and Science University, 3161 SW Pavilion Loop, Portland, OR 97239, USA; [e] Oregon Health and Science University, 3181 SW Sam Jackson Park Road, Portland, OR 97239, USA
* Corresponding author.
E-mail address: erinkh@stanford.edu

Anesthesiology Clin 41 (2023) 121–140
https://doi.org/10.1016/j.anclin.2022.11.004
1932-2275/23/

These strategies are now frequently referred to as lung-protective ventilation (LPV) and are distinctively different from the historical large TVs of 10 to 12 mL/kg used intraoperatively to promote lung recruitment and provide optimal oxygenation. With the growing evidence to support LPV in the management of ARDS in critically ill patients, anesthesiologists and intensivists have translated these strategies for the operating room (OR) in efforts to minimize postoperative pulmonary complications (PPCs) and prevent ventilator-induced lung injury (VILI). However, despite a solid trend in intraoperative ventilator strategies suggesting practice has changed, such as decreased TV[2] and the increased use of positive-end-expiratory pressure (PEEP)[3] during the past decade, the evidence for specific intraoperative lung-protective ventilation (IOLPV) strategies that parallel those in the intensive care unit (ICU) remains incomplete.

As clinicians are faced with decisions regarding which strategies are beneficial in the OR versus the ICU, there are a growing number of critically ill patients that require surgical and procedural interventions during their hospital course. For simplicity of intraoperative management, there is an understandable desire to standardize mechanical ventilation for all patients undergoing surgery, yet there is evidence that this standardized approach may not be optimal or may even be detrimental depending on patient characteristics and surgical conditions.[4] Furthermore, selective targeting of a fixed TV, airway pressure, or gas exchange value may conflict with other protective ventilation goals.[5] Importantly, the stress and strain applied to the lung are not directly measured with standard LPV settings but are inferred from respiratory mechanics. Limitations of intraoperative mechanical ventilators, decreased access to ancillary staff and equipment, dynamic physiologic and positional changes occurring during surgery, in addition to the heterogeneity of the critically ill patient population, are all frequent barriers to implementing a single IOLPV framework for all ICU patients in the OR. Based on these challenges, an individualized approach to intraoperative mechanical ventilation that combines advanced monitoring tools and targets is increasingly becoming a point of focus for reducing PPCs.[6–9]

BACKGROUND

Deleterious outcomes of positive pressure ventilation (PPV) are not new concepts. Well before and directly contributing to the motivation for the landmark ARDSnet study,[1] Ventilator-induced lung injury (VILI) is described in reports of human disease following PPV as well as being studied in animal models preceding this and the term “respirator lung” was coined for patients exhibiting evidence of lung tissue disruption following mechanical ventilation.[10] Evidence of lung tissue damage, pulmonary edema, and development of hyaline membranes as precursors of pending severe and potentially life-threatening lung disease is present in the literature from the 1960s

Box 1
Definitions for the underlying pathophysiology of ventilator-induced lung injury

Barotrauma: Elevated pressure applied to the airways and alveoli affecting the microvasculature of the lung.

Volutrauma: Due to the overdistension of the respiratory apparatus, even in the absence of elevated pressure.

Atelectrauma: Repetitive opening and closing of small airways and alveoli or frequent atelectasis.

Biotrauma: The presence of a panoply of inflammatory substances that results in alveolar damage.

and 1970s.[11,12] Currently, 4 classical concepts for the underlying cause of VILI persist and are further defined in **Box 1**.

Studies focusing on barotrauma revealed that the amount of distension[12] and the transpulmonary pressure (airway pressure–pleural pressure) are both of importance.[13] For example, subjects with low airway but high transpulmonary pressure due to air hunger or significant spontaneous respiratory effort can generate significant gradients associated with lung injury.[14] Similar to barotrauma, but more specifically related to damage resulting from overdistension of alveoli, high volumes during mechanical ventilation lead to alveolar rupture and potentially large air leak.[13,15,16] Just as overdistension of alveoli causes epithelial barrier disruption, repetitive opening and closing of the distal alveoli similarly results in the development of injury from pulmonary edema, epithelial cell dislodgement, and ultimately development of hyaline membranes.[12] PEEP has been shown to reduce this cyclic opening and closing and helps to minimize atelectrauma.[17,18] Indeed, utilization of PEEP to maintain respiratory airway recruitment is now nearly ubiquitous following multiple publications and has been suggested as yet another basis for increased survival in patients with ARDS requiring mechanical ventilation.[19] In a fourth mechanism, stimulation of the inflammatory cytokines leads to an upregulation of hypertrophy and/or hyperplasia of airway epithelium and eventual pulmonary remodeling.[20,21] Notable substances include TNF-alpha, IL-8, and IL-6, and patients prescribed lung-protective ventilation seem to show reduced levels of these cytokines.[22]

In terms of mitigation of VILI, current therapy includes application of reduced lung volumes,[1] reducing airway pressure to the minimum required to provide adequate gas exchange, titration of ventilator settings to transpulmonary pressure as assessed through esophageal pressure monitoring,[23] prone positioning,[24,25] and finally neuromuscular blockade in critically ill patients requiring mechanical ventilation.[26] With studies providing evidence of lung injury through altered structure and ultimately function, the clinician is left without doubt that mechanical ventilation, although lifesaving and often necessary in the OR and the ICU, must be tailored to the individual patient just as any other therapy.

DISCUSSION

The goal of intraoperative mechanical ventilation management is to optimize lung recruitment without overdistending compliant alveoli. In the critically ill patient, the low TV strategy has proven beneficial in preventing mechanisms of VILI that result in improved outcomes. Similarly, low TV ventilation (<8 mL/kg) versus high (>8 mL/kg) with general anesthesia (GA) has been associated with a decrease in PPCs.[27–30] Going beyond low TV as the solo physiologic target for LPV and instead focusing on individualized targets for mechanical ventilation based on physiologic principles and dynamic monitoring may provide more effective intraoperative ventilation and reduce the occurrence of VILI.

ADVANCED PHYSIOLOGIC TARGETS

Alveolar Recruitment

Most patients develop atelectasis during anesthesia and surgery, the extent of which is determined by the type and duration of surgery, surgical technique, positioning, and underlying medical conditions.[31] PEEP can be used to prevent atelectrauma by alveolar recruitment. However, too much PEEP can have a hemodynamic effect, cause overdistention of aerated alveoli leading to increased dead space and shunt, and increased risk of cor pulmonale.[32] PEEP must be carefully titrated to balance the risk/benefit ratio. This approach has been described using P:F tables,[32] stepwise

recruitment maneuvers,[33] and the use of advanced monitoring techniques described below.[32,34,35]

The use of PEEP alone cannot reopen all collapsed alveoli, so it is essential to use a recruitment maneuver (RM) to enable a complete reopening. Several methods for performing RMs have been described in the literature.[36] Most commonly, RMs are performed manually using the "bag squeezing" method of applying and holding a set inflation pressure for a specific duration of time using the airway pressure-limiting valve of the anesthesia machine.[37] However, ventilator-driven RMs are preferred to minimize the loss of PPV when switching back to the ventilator. Provided there are no contraindications, an inspiratory pressure of 40 cmH_2O for 7 to 8 seconds is likely to result in full recruitment in most nonobese patients with healthy lungs.[38,39] Higher pressures and longer times may be needed for certain patients. For anesthesia ventilators that allow pressure-controlled ventilation, RMs can be performed by increasing PEEP up to 20 cmH_2O in steps of 5 cmH_2O (30–60 seconds per step) while maintaining a constant driving pressure of 15 to 20 cmH_2O.[37] Although RMs have the potential to improve respiratory mechanics and gas exchange, they also have the potential to increase lung injury depending on the clinical circumstances.[40] Consequently, it is important to assess the extent of atelectasis and monitor the response when performing RMs. The recruitment-to-inflation ratio is a recently proposed approach to estimate recruitability at the bedside.[41]

Driving Pressure

Driving pressure (DP) is defined as the difference between plateau pressure and PEEP and is linearly related to lung strain.[42] Retrospective studies have shown that DP is related to mortality in patients with ARDS even among those who received traditional protective ventilation.[43,44] The threshold value of DP for higher mortality in patients with ARDS is approximately 15 cmH_2O, and each 1-cmH_2O increase of DP was associated with a 5% increment in mortality. Higher DP values have also been associated with increased mortality in patients receiving pressure support ventilation.[45] In surgical patients, a meta-analysis of 17 randomized controlled trials found that intraoperative high driving pressure was associated with the development of PPCs, whereas no association was found with TV and PEEP.[46] The deleterious effect of DP is believed to result from the concept of "functional lung size"—the volume of aerated lung available for ventilation. "Functional lung size" is reduced in patients with lung pathologic conditions such as atelectasis, consolidation, effusion, or fibrosis. Therefore, if lungs are either overdistended or underventilated in relation to their "functional lung size," DP will increase. It has been suggested that DP may be used to set PEEP because the best compromise between overinflation and recruitment is determined at the lowest DP.[47] However, although studies clearly show that elevated DP is associated with increased complications, they do not confirm that active control of DP improves outcomes. Although a causal effect has not been demonstrated, it has been recommended that at least for patients with ARDS, DP should be targeted less than 13 cmH_2O.[48]

Stress Index

Analysis of the pressure–time curve during volume control ventilation can provide useful information to help set the ventilation parameters.[49] During inspiration in volume control ventilation with constant airflow, the airway pressure–time relationship can be described by the power equation[5]:

$$P_{P\text{-}T} = a \times t^{SI} + c,$$

where the coefficient *a* represents the slope of the pressure time ($P_{P\text{-}T}$) curve at a given time of measurement *t*, and *c* is the pressure at the initiation of inspiration. The constant SI, referred to as the "stress index," is a number that describes the shape of $P_{P\text{-}T}$ curve.

Linearity of the $P_{P\text{-}T}$ curve (SI = 1) denotes compliance during TV insufflation, which is minimally injurious. Nonlinearity of the pressure–time curve denotes a nonconstant compliance during TV insufflation. If compliance increases during inspiration, as occurs with intratidal lung recruitment, the slope of the pressure–time curve decreases over time, resulting in a downward concavity (SI < 1). Implementation of increased PEEP to avoid the cyclic opening and closing of respiratory units, a mechanism of VILI, is beneficial in this instance. In contrast, if compliance decreases during inspiration, as suggested by an upward concavity of the pressure–time curve (SI > 1), this suggests that the lung is cyclically overdistended during inspiration. In this case, a reduction of PEEP and/or TV might be warranted. Use of the SI allows adjustment of the ventilatory settings to respiratory system characteristics of the patient, modifying VT and PEEP. Although measuring the SI requires complex calculations that are clinically onerous, it can be easily estimated by visualizing the $P_{P\text{-}T}$ curve and is demonstrated in **Fig. 1**.[50,51]

Mechanical Power

Mechanical power (MP) is a summary construct that attempts to relate the different ventilatory parameters set by the clinician at the bedside to the amount of energy transferred from the mechanical ventilator to the respiratory system.[52] MP can be estimated using a simplified equation of motion:

$$MP = RR \times \Delta V^2 \times \{(0.5 \times Ers + RR \times (1 + I{:}E)/60 \times I{:}E \times Raw) + \Delta V \times PEEP),$$

where ΔV is tidal change in lung volume, RR is respiratory rate, Ers is respiratory system elastance, and Raw is airway resistance, and I:E is the inspiratory–expiratory ratio.

The MP equation illustrates the relative importance of each respiratory variable on the energy delivered to the lungs during mechanical ventilation. For example, the

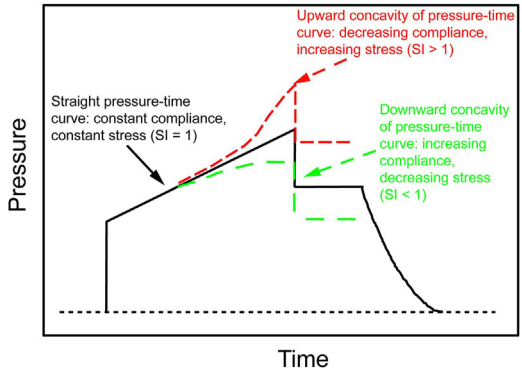

Fig. 1. A dynamic airway pressure during volume control ventilation with a constant inspiratory flow. The stress index (SI) is derived from changes in the slope of the pressure time during inspiration. Upward concavity of the pressure–time curve reflects decreasing compliance (overdistension, SI > 1) while downward concavity of the pressure–time curve indicates increasing compliance (atelectasis, SI < 1). (*From* [Kallet RH. Should PEEP Titration Be Based on Chest Mechanics in Patients with ARDS? *Respir Care*. Jun 2016;61(6):876-90]; with permission.)

effect of TV, which is squared in the MP calculation, is predominant. The effect of PEEP is dichotomous: PEEP directly increases the MP but can also indirectly reduce it through a reduction in Ers. The MP equation also illustrates that the respiratory rate is linearly related to the amount of the energy delivered to the lungs. Studies have reported that increasing values of MP are associated with an increased risk of lung injury.[53,54]

The MP calculation is too cumbersome for clinical use and simpler formulas are being evaluated.[55] It is also important to recognize that despite low MP values, lung damage is still possible with inhomogeneous ventilation where atelectasis and hyperinflation simultaneously coexist.[6]

Dead Space

An important determinant of the appropriate size of the delivered TV during mechanical ventilation is the size of the dead space—the volume of inhaled gas that does not take part in gas exchange.[56] Dead space is divided into the anatomic dead space—which exists in the large and small airways that do not normally participate in gas exchange—and the alveolar dead space, which results when there is absence of blood flow to an area of lung that is still receiving ventilation. Physiologic dead space, the sum of anatomical and alveolar dead space, is a global measure of the efficiency of the lung function. It has been associated with outcome in patients with respiratory failure and may be helpful for selecting optimal PEEP.[9,57] However dead space is not routinely measured in anesthetic practice, due to difficulties in interpreting capnograms and in calculation methods. Use of minute ventilation is unable to adequately describe ventilation efficiency because it does not distinguish between alveolar and anatomic dead space ventilation. Volumetric capnography (VCap), which measures the volume of expired CO_2 in one single breath, is a reliable real-time method for measuring dead space. In addition, VCap provides information about pulmonary perfusion, end-expiratory lung volume, and pulmonary ventilation inhomogeneities, which can be used for optimization of ventilation at the bedside.[58–60] Although further investigation is needed to establish the optimal use of VCap in the intraoperative setting, it is a potentially useful noninvasive tool to measure dead space and optimize intraoperative ventilation.

ADVANCED MONITORING TOOLS

Electrical Impedance Tomography

Electrical impedance tomography (EIT) is a noninvasive, radiation-free portable monitoring technique that provides images based on the electrical conductivity of tissue in the chest. Electrodes are placed on the chest wall, which record the surface voltage after the repeated application of a small amount of electrical current. The changes of electrical impedance over time are displayed dynamically in color-code images. By imaging breath-by-breath changes in ventilation distribution, EIT can be used intraoperatively to dynamically optimize ventilator settings.[61] EIT measurements of TV and ventilation distribution have been validated as accurate surrogates in comparison to CT scan and nitrogen washout, respectively.[62] EIT monitoring can identify regional ventilation heterogeneity, overdistention, and atelectasis, that are otherwise not identifiable by traditional protective ventilator-based metrics.

EIT helps inform the mechanical compromise between ventilation of nondependent and dependent lung regions, minimizing both overdistension and collapse. These beneficial effects are more pronounced in obese patients and those undergoing interventions that impair normal respiratory mechanics (eg, laparoscopy procedures or

Trendelenburg positioning).[63] A variety of EIT-derived indices have been proposed to quantify temporal and spatial ventilation heterogeneity including the "global inhomogeneity index," "regional ventilation delay," and "dynamic relative regional strain." Lung perfusion monitoring is another important feature of EIT that can be evaluated during general anesthesia. An IV injection of hypertonic saline during an expiratory breath-hold allows the calculation of pulmonary perfusion through impedance time-curves. Comparisons of impedance data for both ventilation and perfusion can then be analyzed and ventilator strategies can be altered based on knowledge of ventilation/perfusion mismatch.[64] Although the usefulness of EIT has been highlighted by a growing body of literature; limitations to its use include lower spatial resolution; lack of intrapatient and interpatient reproducibility secondary to variations in electrode placement; and deterrence due to setup time, equipment costs, and training of personnel.

Esophageal Manometry

Esophageal manometry is a clinical method used to separate the pressure applied to the respiratory system (P_{aw}) into the component distending the chest wall (ie, pleural pressure, P_{pl}), and that distending the lung transpulmonary pressure (P_L).[65,66] Transpulmonary pressure is defined as the difference between the airway pressure and the pleural pressure.

$$P_L = P_{aw} - P_{pl}$$

Esophageal manometry estimates the P_{pl} through an air-filled balloon catheter inserted in the esophagus. Although esophageal manometry is best known for its role in guiding mechanical ventilation in patients with ARDS,[34] it has also been used in the OR to optimize PEEP instead of relying on standard protective parameters that target P_{aw} alone. To prevent atelectasis, it has been proposed to adjust PEEP such that expiratory transpulmonary pressure is slightly positive, so as to ensure that the lung (if recruitable) is maintained open.[66] To prevent injury from overdistension, attempts are also made to limit the inspiratory transpulmonary pressure.

Esophageal manometry can be used not only to monitor respiratory system mechanics during controlled ventilation but also to monitor patient's respiratory muscle activity during spontaneous breathing. Although evidence-based guidelines recommend limiting inspiratory plateau pressure (P_{plat}) to 30 cmH_2O especially in ARDS; however, P_{aw} cannot be measured during normal spontaneous breathing. In contrast, P_L can be measured during spontaneous breathing because it is calculated based on both P_{aw} and P_{pl}. Studies in healthy individuals indicate that a P_L of 25 cmH_2O is the upper limit encountered by the lungs in normal life but it is unclear whether this limit is safe in injured lungs, and, a lower threshold than that experienced in healthy breathing may be required.[67]

Despite these potential benefits of esophageal manometry, only limited studies have demonstrated a positive influence of esophageal manometry on patient outcomes.[68] In the OR setting, esophageal manometry may be especially helpful for selecting PEEP in patients with chest-wall abnormalities, such as those with obesity, or with surgical conditions such as increased intra-abdominal pressure due to laparoscopy or Trendelenburg positioning. Setting a desired target for transpulmonary pressures is another proposed method for determining appropriate TVs based on patient's respiratory mechanics.[69] **Fig. 2** demonstrates an example of using esophageal manometry and EIT together to optimize mechanical ventilation during pneumoperitoneum and Trendelenburg positioning in an obese patient.

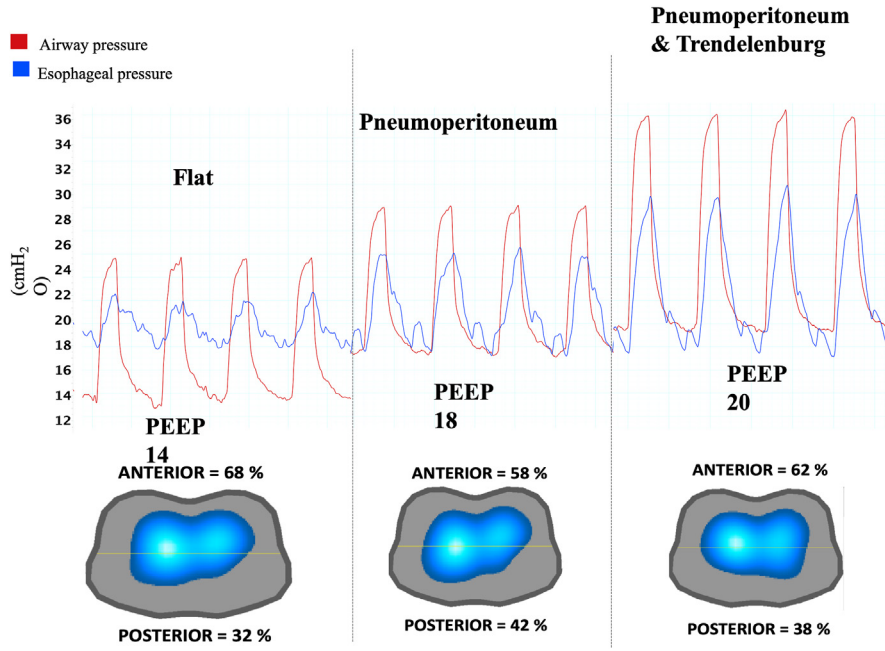

Fig. 2. The use of esophageal manometry and electrical impedance for intraoperative mechanical ventilation optimization in an obese patient.

Lung Ultrasound

Lung ultrasonography (LUS) is a noninvasive bedside tool that can quantify aerated lung mass and provide real-time information during mechanical ventilation.[70] In the perioperative setting, LUS has been used to dynamically detect the development of intraoperative atelectasis, alveolar consolidation, as well as diaphragmatic dysfunction and weakness.[71–73] LUS can be used to assess PEEP-induced lung recruitment, enabling optimization of the ventilatory settings. It can also help discriminate between a cardiac, lung parenchymal, or diaphragmatic cause of loss of lung aeration and, as a consequence, help to determine the most appropriate approach to management.[74] Although lung aeration reaeration can be evaluated using LUS, the ability to predict lung overinflation has been more challenging and the source of ongoing investigation.[75,76]

METHODS TO INCREASE ADHERENCE TO INTRAOPERATIVE LUNG-PROTECTIVE VENTILATION

With multiple physiologic targets, equations, and studies to recall, creating an individualized approach to mechanical ventilation in the OR can be cumbersome and can be limited by the individual's education and comfortability of IOLPV. IOLPV strategies that institute physiologic TVs (6–8 mL/kg cmH_2O) and avoid zero PEEP settings can be facilitated by institutional quality improvement measures. Interventions that have shown improvement in the adherence to IOLPV include the removal of older anesthesia machines,[77] modification of default anesthesia ventilator settings,[78] and near real-time feedback with individualized performance data regarding personal adherence with a peer comparison.[79] For the critically ill patient requiring mechanical

ventilation in the OR, the use of a standardized hand-off tool to incorporate mechanical ventilation goals and targets between the ICU and OR team can be instrumental in continuing LPV in the OR setting.

CLINICAL RELEVANCE

Risk Evaluation and Prediction Scores

Selection of an individualized intraoperative ventilation strategy begins with an awareness of the factors that pose the greatest risk for PPCs. Acknowledging known risk factors and using risk prediction models can be useful, particularly in patients that seem to have healthy lungs despite being at risk for PPC or critical illness.[80,81] Recent studies show that patients with a higher risk of PPCs are not routinely receiving IOLPV in the OR.[82] **Table 1** demonstrates the use of 3 different prediction/risk scores available: risk of PPC in patients undergoing surgical procedures (ARISCAT),[83] risk of ALI in-patients with predisposing conditions (lung injury prediction score [LIPS]),[84] and hospitalized patients at risk for progression to PPV due to worsening pulmonary dynamics (early acute lung injury [EALI]).[85] Incorporating these models into your intraoperative mechanical ventilation plan can help minimize "second-hit" exposures in conjunction with a LPV strategy.[84]

Induction

Although 20% to 40% of ICU patients require mechanical ventilation, it is not uncommon to encounter spontaneously breathing critically ill patients that need a life-sustaining intervention in the operating suite to advance care. In these cases, it is vital to remember that protective ventilation begins with induction. Atelectasis occurs in 90% of patients undergoing GA, and it can persist for weeks postoperatively.[27] This is usually tolerated well by young, otherwise healthy patients. However, patients who are aged older than 50 years or who have a body mass index (BMI) greater than 40 kg/m^2, an American Society of Anesthesiologists physical status greater than II, or obstructive sleep apnea may have less tolerance for the decreased functional residual capacity (FRC), shortening the time allowable for intubation. Supine positioning during anesthetic induction results in cephalad displacement of abdominal contents and compression of dependent lung regions. The 30-degree head-up and reverse Trendelenburg positions are associated with less reduction in FRC and should be used during anesthetic induction especially in obese individuals.[27] Critically ill patients are at a high risk for airway complications due to pathophysiologic alterations recently defined as the "physiologically difficult airway," which can hinder optimal intubation times.[86] There is some literature to support the use of noninvasive positive pressure ventilation during induction to reduce atelectasis, minimize desaturations, and allow more time for intubation.[27,86]

Sepsis

Sepsis remains one of the leading causes of ICU admission. Timely source control remains vital to standard treatment. Adequate source control within 6 hours of sepsis onset is associated with reduced risk-adjusted odds of 90-day mortality.[87] One-third of hospitalized patients with sepsis will undergo source-control procedures,[88] and although the use of minimally invasive procedures has increased, anesthetic consideration and ventilation strategies are necessary for many of these procedures. Sepsis and septic shock are known risk factors for ARDS.[84] The requirement for mechanical ventilation in the setting of sepsis can range from airway protection for procedures or altered mental status, to acute respiratory failure secondary to pneumonia,

Table 1
Risk and prediction models for postoperative pulmonary complications and acute lung injury

Assess Respiratory Risk in Surgical Patients in Catalonia (ARISCAT) Risk Score		LIPS		EALI Score	
Parameters	**Score**	**Predisposing Conditions**	**LIPS Points**	**Component**	**Points**
Age (y)		Shock	2	O_2 requirement	
≤50	0	Aspiration	2	>2–6 L/min	1
51–80	3	Sepsis	1	>6 L/min	2
>80	16	Pneumonia	1.5	Tachypnea (RR > 30)	1
Preop S_pO_2[a]		High-risk surgery[b]		Immune suppression	1
≥96%	0	Orthopedic spine	1		
91%–95%	8	Acute abdomen	2	EALI score greater than or equal to 2 identified patients who progressed to ALI and the need for PPV (median time of progression 20 h)	
≤50%	24	Cardiac	2.5		
Respiratory infection last 30d		Aortic vascular	3.5		
No	0	High-risk trauma			
Yes	17	Traumatic brain injury	2		
Surgical incision		Smoke inhalation	2		
Peripheral	0	Near drowning	2		
Upper abdominal	15	Lung contusion	1.5		
Intrathoracic	24	Multiple fractures	1.5		
Duration of surgery		Modifiable risk factors			
<2	0	Alcohol abuse	1	LIPS >4 was associated with an increased frequency of ALI/ARDS with a positive likelihood ration of 3.10	

2–3	16	Obesity (body mass index >30)	1
> 3	23	Hypoalbuminemia	1
Emergency procedure		Chemotherapy	1
No	0	$F_iO.35$ (4 L/min)	2
Yes	8	Tachypnea (RR > 30)	1.5
ARISCAT has three levels of risk for PPC: <26 points, low (1.6%); 26–44 points, moderate (13.3%); and > 45 points, high risk (42.1%)		SpO_2 < 95%[a] Acidosis (pH<7.35) Diabetes mellitus[c]	1 1.5 -1

[a] Arterial oxyhemoglobin saturation by pulse oximetry.
[b] Add 1.5 points if emergency surgery.
[c] Only if sepsis.

or to sepsis-induced ARDS. A multidisciplinary team coordination for induction and intubation is important given the possibility of hypoxemia, hypotension, and cardiac collapse that can result in the setting of a physiologically difficult airway. Given the high possibility of a metabolic acidemia at the time of induction and intubation, one must take caution of allowing permissive hypercapnia in the setting of low TVs in at risk patients, resulting in a worsening acidosis.[89] The Surviving Sepsis Campaign Guidelines outline mechanical ventilation strategies for septic patients, which are summarized in **Box 2**.[90] Many of the recommendations parallel to those already discussed, with the exception of a suggestion to use low TV compared with high TV ventilation for adults with sepsis-induced respiratory failure (without ARDS). While stating that the evidence is low and the recommendation is weak, given that sepsis is an independent risk factor for the development of ARDS, they recommend utilizing low TV strategies to avoid the underuse of or the delayed implementation of LPV in an at-risk population.[90]

Acute Respiratory Distress Syndrome

ARDS affects approximately 200,000 patients each year in the United States and results in nearly 75,000 deaths annually.[91] The clinical trials during the past 50 years exploring ways to prevent, mitigate, and treat ARDS are extensive and beyond the scope of this article. However, as this article does focus on the intraoperative strategies for critically ill patients, many of the parameters that were already explored are relevant to IOLPV in patients meeting criteria for the definition of ARDS. Institution of low TVs, high PEEP, and prone positioning for more than 12 hours have shown beneficial results in the outcomes of patients with ARDS and should be incorporated into IOLPV protocols to minimize VILI.[91,92] Although proning patients in the OR may not be practical, considerations of performing bedside interventions in the ICU to limit interruptions in proning protocols could be considered. Anesthesiologists frequently use intraoperative neuromuscular blocking agents (NMBA) to facilitate intraoperative

Box 2
Surviving sepsis campaign guidelines for ventilator strategies in adults with sepsis

In sepsis-induced respiratory failure (without ARDS):
- Suggest using low TV as compared with high TV ventilation
  - Low quality evidence, weak recommendation

In sepsis-induced ARDS:
- Recommend using a low TV ventilation strategy (6 mL/kg) over a high TV strategy (>10 mL/kg)
  - High quality evidence, strong recommendation

In sepsis-induced severe ARDs:
- Recommend using an upper limit goal for plateau pressures of 30 cmH_2O
  - Moderate quality evidence, strong recommendation

In sepsis-induced moderate–severe ARDS:
- Suggest using higher PEEP over lower PEEP
  - Moderate quality weak recommendation
- Suggest using traditional recruitment maneuvers
  - Moderate quality weak recommendation
- Suggest using intermittent neuromuscular blocking agents (NMBA) over NMBA continuous infusion
  - Moderate quality weak recommendation
- Suggest using veno-venous extracorporeal membrane oxygenation when conventional mechanical ventilation fails
  - Low quality of evidence weak recommendation

ventilator synchrony and optimize surgical conditions. However, the most recent studies suggest that prolonged NMBA are no longer beneficial for ARDS and new recommendations regard limiting their use or implementing intermittent boluses over continuous infusions.[93] The OR and ICU team should coordinate goals for NMBA before transport and incorporate these new guidelines in the OR when feasible.

Special Surgical Cases and Patient Populations

Patient positioning and surgical conditions are important to consider in determining an LPV strategy. Laparoscopic surgery can have negative effects on respiratory mechanics resulting from the pneumoperitoneum, which reduces FRC and promotes atelectasis formation. Pneumoperitoneum also results in reduced compliance of the respiratory system such that a greater amount of pressure will be required to expand the chest wall to achieve a given TV. Many laparoscopic procedures also use the Trendelenburg position that further increases the transmission of intra-abdominal pressure to the chest. Other unique considerations include lateral positioning and single lung ventilation, which also result in changes in lung compliance, resistance, and in TV distribution. The PROTHOR study found a decrease in PPCs in one-lung ventilation with the use of low TV ventilation (6 mL/kg PBW), RMs, and high PEEP.[94] In addition, compliance of the ventilated lung was improved and as a result, driving pressure was decreased. Other trials, such as the iPROVE-OLV are ongoing.[95]

Patients with a BMI greater than 35 can develop rapid atelectasis, a decrease in FRC, and are susceptible to positioning changes in the OR. A recent study in JAMA compared the use of high PEEP (12 cmH_2O) with RMs with low PEEP (4 cmH_2O) with no RMs. Both groups received low TV ventilation of 7 mL/kg PBW in obese (BMI >35) patients undergoing noncardiac surgery. No differences in PPCs were found. The higher PEEP group had lower driving pressures but they were limited by hemodynamic instability.[96] A secondary analysis of this same cohort compared the fixed PEEP strategy to an individualized PEEP strategy using EIT.[97] The individualized PEEP was superior to either fixed low levels or hither level PEEP with regards to oxygenation, driving pressures, and indices of regional ventilation but did not show a difference in PPCs. Ventilator settings often need to be readjusted in response to surgical conditions, adding complexity to the ventilatory management of patients in the OR, and further studies may be needed to elucidate optimization of intraoperative mechanical ventilation in special patient populations.

RECOMMENDATIONS FOR INTRAOPERATIVE LUNG PROTECTIVE VENTILATION

Recent guidelines and several reviews focusing on intraoperative ventilation for patients with and without ARDS have recently been published.[7,27] Based on these publications and the prior discussion in this article, some recommendations for an individualized approach to IOLPV are provided.

Ventilatory parameters should be selected and titrated based on close monitoring of targeted physiologic variables and individualized goals. Although low TV and reduced airway pressures are standard components of LPV, further individualization of ventilation may be necessary based on patient characteristics and surgical conditions. Lung recruitability is essential to identify to determine the potential benefit of RMs and PEEP titration. DPs provide a target to adjust TV and possibly to optimize PEEP. For most patients, DP should be maintained less than 13 cmH_2O. Advanced monitoring tools including EIT, esophageal manometry, and LUS require additional effort and skill for interpretation but should be considered for patients and during surgical procedures that compromise respiratory mechanics and make standard interpretation difficult. Measures including

mechanical power, stress index, and dead space provide additional insight into physiology of mechanical ventilation and may provide targets for further optimization.

SUMMARY

Based on the past 20 years of evidence for LPV in ARDS, anesthesiologists have an opportunity to advance intraoperative ventilatory management of critically ill patients in the OR. Delineating which parameters and strategies are best used in the OR versus the ICU will still require more investigation; however, the trend for low TVs, adequate PEEP, and driving pressure targets have gained traction as strategies to prevent PPCs and ARDS. Implementing educational strategies using the EMR and feedback dashboards and resetting default ventilator settings are 2 methods that can be used to change practice. Incorporating more advanced monitoring tools and assessments of respiratory mechanics may help anesthesiologists improve respiratory care provided at the individual level.

CLINICS CARE POINTS

- When implementing a LPV strategy in the OR include both low TVs and the use of PEEP in ventilator settings and avoid the use of low TVs without PEEP given the risk of atelectrauma.
- When monitoring driving pressure in the OR, target driving pressures that increase compliance or to a goal of less than 13.
- When performing a recruitment maneuver in the OR, look for evidence of atelectasis and recruitability by using the stress index and avoid using recruitment maneuvers in patients with overdistension.
- When performing recruitment maneuvers in the OR, consider setting the peak inspirator pressure at 40 cmH_2O for 7 to 8 seconds or an upward titration of PEEP up to 20 cmH_2O in a pressure-controlled mode but avoid the "bag squeezing" technique to minimize the loss of positive pressure ventilation.
- When inducing anesthesia and providing mechanical ventilation for patients with obesity, limiting atelectasis starts with induction and patients should be intubated in the 30-degree head-up and reverse Trendelenburg position.
- When intubating critically ill patients in the OR at risk for a physiological difficult airway, use noninvasive mechanical ventilation during induction.
- If your patient presents in sepsis or with septic shock, use low TV strategies in the OR given the high risk of ARDS in patients with sepsis.
- When caring for patients with sepsis or septic shock who require mechanical ventilation in the OR, avoid worsening acidemia with permissive hypercapnia.
- If a patient undergoing laparoscopic surgery develops worsening gas exchange with insufflation, increase PEEP and try recruitment maneuvers and consider a change in position or surgical technique if unsuccessful.

REFERENCES

1. Brower RG, Matthay MA, Morris A, et al. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000;342(18):1301–8.
2. Schaefer MS, Serpa Neto A, Pelosi P, et al. Temporal changes in ventilator settings in patients with uninjured lungs: a systematic review. Anesth Analg 2019; 129(1):129–40.

3. Bender SP, Paganelli WC, Gerety LP, et al. Intraoperative Lung-Protective Ventilation Trends and Practice Patterns: A Report from the Multicenter Perioperative Outcomes Group. Anesth Analg 2015;121(5):1231–9.
4. Kirov MY, Kuzkov VV. Protective ventilation from ICU to operating room: state of art and new horizons. Korean J Anesthesiol 2020;73(3):179–93.
5. Ball L, Costantino F, Fiorito M, et al. Respiratory mechanics during general anaesthesia. Ann Transl Med 2018;6(19):379.
6. Fogagnolo A, Montanaro F, Al-Husinat Li, et al. Management of Intraoperative Mechanical Ventilation to Prevent Postoperative Complications after General Anesthesia: A Narrative Review.
7. Meier A, Hylton D, Schmidt UH. Intraoperative Ventilation in the High-Risk Surgical Patient. Respir Care 2021;66(8):1337–40.
8. Eikermann M, Kurth T. Apply Protective Mechanical Ventilation in the Operating Room in an Individualized Approach to Perioperative Respiratory Care. Anesthesiology 2015;123(1):12–4.
9. Nieman GF, Satalin J, Andrews P, et al. Personalizing mechanical ventilation according to physiologic parameters to stabilize alveoli and minimize ventilator induced lung injury (VILI). Intensive Care Med Exp 2017;5(1):8.
10. Respirator lung syndrome. Minn Med 1967;50(11):1693–705.
11. Ashbaugh DG, Bigelow DB, Petty TL, et al. Acute respiratory distress in adults. Lancet 1967;2(7511):319–23.
12. Webb HH, Tierney DF. Experimental pulmonary edema due to intermittent positive pressure ventilation with high inflation pressures. Protection by positive end-expiratory pressure. Am Rev Respir Dis 1974;110(5):556–65.
13. Slutsky AS, Ranieri VM. Ventilator-induced lung injury. N Engl J Med 2013; 369(22):2126–36.
14. Yoshida T, Uchiyama A, Matsuura N, et al. Spontaneous breathing during lung-protective ventilation in an experimental acute lung injury model: high transpulmonary pressure associated with strong spontaneous breathing effort may worsen lung injury. Crit Care Med 2012;40(5):1578–85.
15. Beitler JR, Malhotra A, Thompson BT. Ventilator-induced Lung Injury. Clin Chest Med 2016;37(4):633–46.
16. Albert RK. The role of ventilation-induced surfactant dysfunction and atelectasis in causing acute respiratory distress syndrome. Am J Respir Crit Care Med 2012; 185(7):702–8.
17. Caironi P, Cressoni M, Chiumello D, et al. Lung opening and closing during ventilation of acute respiratory distress syndrome. Am J Respir Crit Care Med 2010; 181(6):578–86.
18. Amato MB, Barbas CS, Medeiros DM, et al. Effect of a protective-ventilation strategy on mortality in the acute respiratory distress syndrome. N Engl J Med 1998; 338(6):347–54.
19. de Durante G, del Turco M, Rustichini L, et al. ARDSNet lower tidal volume ventilatory strategy may generate intrinsic positive end-expiratory pressure in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 2002; 165(9):1271–4.
20. Tremblay L, Valenza F, Ribeiro SP, et al. Injurious ventilatory strategies increase cytokines and c-fos m-RNA expression in an isolated rat lung model. J Clin Invest 1997;99(5):944–52.
21. Curley GF, Laffey JG, Zhang H, et al. Biotrauma and Ventilator-Induced Lung Injury: Clinical Implications. Chest 2016;150(5):1109–17.

22. Ranieri VM, Suter PM, Tortorella C, et al. Effect of mechanical ventilation on inflammatory mediators in patients with acute respiratory distress syndrome: a randomized controlled trial. JAMA 1999;282(1):54–61.
23. Baedorf Kassis E, Schaefer MS, Maley JH, et al. Transpulmonary pressure measurements and lung mechanics in patients with early ARDS and SARS-CoV-2. J Crit Care 2021;63:106–12.
24. Sud S, Friedrich JO, Taccone P, et al. Prone ventilation reduces mortality in patients with acute respiratory failure and severe hypoxemia: systematic review and meta-analysis. Intensive Care Med 2010;36(4):585–99.
25. Piedalue F, Albert RK. Prone positioning in acute respiratory distress syndrome. Respir Care Clin N Am 2003;9(4):495–509.
26. Sottile PD, Albers D, Moss MM. Neuromuscular blockade is associated with the attenuation of biomarkers of epithelial and endothelial injury in patients with moderate-to-severe acute respiratory distress syndrome. Crit Care 2018;22(1):63.
27. Young CC, Harris EM, Vacchiano C, et al. Lung-protective ventilation for the surgical patient: international expert panel-based consensus recommendations. Br J Anaesth 2019;123(6):898–913.
28. Wolthuis EK, Choi G, Dessing MC, et al. Mechanical ventilation with lower tidal volumes and positive end-expiratory pressure prevents pulmonary inflammation in patients without preexisting lung injury. Anesthesiology 2008;108(1):46–54.
29. Yang D, Grant MC, Stone A, et al. A Meta-analysis of Intraoperative Ventilation Strategies to Prevent Pulmonary Complications: Is Low Tidal Volume Alone Sufficient to Protect Healthy Lungs? Ann Surg 2016;263(5):881–7.
30. Serpa Neto A, Hemmes SN, Barbas CS, et al. Protective versus conventional ventilation for surgery: a systematic review and individual patient data meta-analysis. Anesthesiology 2015;123(1):66–78.
31. Hedenstierna G, Edmark L. Mechanisms of atelectasis in the perioperative period. Best Pract Res Clin Anaesthesiol 2010;24(2):157–69.
32. Dianti J, Tisminetzky M, Ferreyro BL, et al. Association of positive end-expiratory pressure and lung recruitment selection strategies with mortality in acute respiratory distress syndrome: a systematic review and network meta-analysis. Am J Respir Crit Care Med 2022;205(11):1300–10.
33. Meade MO, Cook DJ, Guyatt GH, et al. Ventilation strategy using low tidal volumes, recruitment maneuvers, and high positive end-expiratory pressure for acute lung injury and acute respiratory distress syndrome: a randomized controlled trial. JAMA 2008;299(6):637–45.
34. Talmor D, Sarge T, Malhotra A, et al. Mechanical ventilation guided by esophageal pressure in acute lung injury. N Engl J Med 2008;359(20):2095–104.
35. Beitler JR, Sarge T, Banner-Goodspeed VM, et al. Effect of Titrating Positive End-Expiratory Pressure (PEEP) With an Esophageal Pressure-Guided Strategy vs an Empirical High PEEP-Fio2 Strategy on Death and Days Free From Mechanical Ventilation Among Patients With Acute Respiratory Distress Syndrome: A Randomized Clinical Trial. JAMA 2019;321(9):846–57.
36. Hess DR. Recruitment Maneuvers and PEEP Titration. Respir Care 2015;60(11):1688–704.
37. Güldner A, Kiss T, Serpa Neto A, et al. Intraoperative protective mechanical ventilation for prevention of postoperative pulmonary complications: a comprehensive review of the role of tidal volume, positive end-expiratory pressure, and lung recruitment maneuvers. Anesthesiology 2015;123(3):692–713.

38. Rothen HU, Neumann P, Berglund JE, et al. Dynamics of re-expansion of atelectasis during general anaesthesia. Br J Anaesth 1999;82(4):551–6.
39. Tusman G, Groisman I, Fiolo FE, et al. Noninvasive monitoring of lung recruitment maneuvers in morbidly obese patients: the role of pulse oximetry and volumetric capnography. Anesth Analg 2014;118(1):137–44.
40. Fan E, Checkley W, Stewart TE, et al. Complications from recruitment maneuvers in patients with acute lung injury: secondary analysis from the lung open ventilation study. Respir Care 2012;57(11):1842–9.
41. Chen L, Del Sorbo L, Grieco DL, et al. Potential for Lung Recruitment Estimated by the Recruitment-to-Inflation Ratio in Acute Respiratory Distress Syndrome. A Clinical Trial. Am J Respir Crit Care Med 2020;201(2):178–87.
42. Aoyama H, Yamada Y, Fan E. The future of driving pressure: a primary goal for mechanical ventilation? J Intensive Care 2018;6:64.
43. Amato MB, Meade MO, Slutsky AS, et al. Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med 2015;372(8):747–55.
44. Guérin C, Papazian L, Reignier J, et al. Effect of driving pressure on mortality in ARDS patients during lung protective mechanical ventilation in two randomized controlled trials. Crit Care 2016;20(1):384.
45. Bellani G, Grassi A, Sosio S, et al. Driving Pressure Is Associated with Outcome during Assisted Ventilation in Acute Respiratory Distress Syndrome. Anesthesiology 2019;131(3):594–604.
46. Neto AS, Hemmes SN, Barbas CS, et al. Association between driving pressure and development of postoperative pulmonary complications in patients undergoing mechanical ventilation for general anaesthesia: a meta-analysis of individual patient data. Lancet Respir Med 2016;4(4):272–80.
47. Meier A, Sell RE, Malhotra A. Driving pressure for ventilation of patients with acute respiratory distress syndrome. Anesthesiology 2020;132(6):1569–76.
48. Pelosi P, Ball L, Barbas CSV, et al. Personalized mechanical ventilation in acute respiratory distress syndrome. Crit Care 2021;25(1):250.
49. Grasso S, Terragni P, Mascia L, et al. Airway pressure-time curve profile (stress index) detects tidal recruitment/hyperinflation in experimental acute lung injury. Crit Care Med 2004;32(4):1018–27, ad.
50. Sun XM, Chen GQ, Chen K, et al. Stress index can be accurately and reliably assessed by visually inspecting ventilator waveforms. Respir Care 2018;63(9):1094–101.
51. Kallet RH. Should PEEP Titration Be Based on Chest Mechanics in Patients With ARDS? Respir Care 2016;61(6):876–90.
52. Gattinoni L, Tonetti T, Cressoni M, et al. Ventilator-related causes of lung injury: the mechanical power. Intensive Care Med 2016;42(10):1567–75.
53. Giosa L, Busana M, Pasticci I, et al. Mechanical power at a glance: a simple surrogate for volume-controlled ventilation. Intensive Care Med Exp 2019;7(1):61.
54. Karalapillai D, Weinberg L, Neto AS, et al. Intra-operative ventilator mechanical power as a predictor of postoperative pulmonary complications in surgical patients: A secondary analysis of a randomised clinical trial. Eur J Anaesthesiol 2022;39(1):67–74.
55. Silva PL, Ball L, Rocco PRM, et al. Power to mechanical power to minimize ventilator-induced lung injury? Intensive Care Med Exp 2019;7(Suppl 1):38.
56. Robertson HT. Dead space: the physiology of wasted ventilation. Eur Respir J 2015;45(6):1704–16.

57. Morales-Quinteros L, Schultz MJ, Bringué J, et al. Estimated dead space fraction and the ventilatory ratio are associated with mortality in early ARDS. Ann Intensive Care 2019;9(1):128.
58. Suárez-Sipmann F, Villar J, Ferrando C, et al. Monitoring Expired CO. Front Physiol 2021;12:785014.
59. Verscheure S, Massion PB, Verschuren F, et al. Volumetric capnography: lessons from the past and current clinical applications. Crit Care 2016;20(1):184.
60. Suarez-Sipmann F, Bohm SH, Tusman G. Volumetric capnography: the time has come. Curr Opin Crit Care Jun 2014;20(3):333–9.
61. Spinelli E, Mauri T, Fogagnolo A, et al. Electrical impedance tomography in perioperative medicine: careful respiratory monitoring for tailored interventions. BMC Anesthesiol 2019;19(1):140.
62. Rubin J, Berra L. Electrical impedance tomography in the adult intensive care unit: clinical applications and future directions. Curr Opin Crit Care 2022;28(3):292–301.
63. Ukere A, März A, Wodack KH, et al. Perioperative assessment of regional ventilation during changing body positions and ventilation conditions by electrical impedance tomography. Br J Anaesth 2016;117(2):228–35.
64. Xu M, He H, Long Y. Lung Perfusion Assessment by Bedside Electrical Impedance Tomography in Critically Ill Patients. Front Physiol 2021;12:748724.
65. Akoumianaki E, Maggiore SM, Valenza F, et al. The application of esophageal pressure measurement in patients with respiratory failure. Am J Respir Crit Care Med 2014;189(5):520–31.
66. Yoshida T, Amato MBP, Grieco DL, et al. Esophageal manometry and regional transpulmonary pressure in lung injury. Am J Respir Crit Care Med 2018;197(8):1018–26.
67. Pham T, Telias I, Beitler JR. Esophageal manometry. Respir Care 2020;65(6):772–92.
68. Cammarota G, Lauro G, Sguazzotti I, et al. Esophageal pressure versus gas exchange to set PEEP during intraoperative ventilation. Respir Care 2020;65(5):625–35.
69. Grieco DL, Chen L, Brochard L. Transpulmonary pressure: importance and limits. Ann Transl Med 2017;5(14):285.
70. Mojoli F, Bouhemad B, Mongodi S, et al. Lung Ultrasound for Critically Ill Patients. Am J Respir Crit Care Med 2019;199(6):701–14.
71. Cylwik J, Buda N. The impact of ultrasound-guided recruitment maneuvers on the risk of postoperative pulmonary complications in patients undergoing general anesthesia. J Ultrason 2022;22(88):e6–11.
72. Umbrello M, Formenti P. Ultrasonographic assessment of diaphragm function in critically ill subjects. Respir Care 2016;61(4):542–55.
73. Moury PH, Cuisinier A, Durand M, et al. Diaphragm thickening in cardiac surgery: a perioperative prospective ultrasound study. Ann Intensive Care 2019;9(1):50.
74. Vetrugno L, Brussa A, Guadagnin GM, et al. Mechanical ventilation weaning issues can be counted on the fingers of just one hand: part 2. Ultrasound J 2020;12(1):15.
75. Tang KQ, Yang SL, Zhang B, et al. Ultrasonic monitoring in the assessment of pulmonary recruitment and the best positive end-expiratory pressure. Medicine (Baltimore) 2017;96(39):e8168.
76. Tonelotto B, Pereira SM, Tucci MR, et al. Intraoperative pulmonary hyperdistention estimated by transthoracic lung ultrasound: A pilot study. Anaesth Crit Care Pain Med 2020;39(6):825–31.

77. Blum JM, Davila V, Stentz MJ, et al. Replacement of anesthesia machines improves intraoperative ventilation parameters associated with the development of acute respiratory distress syndrome. BMC Anesthesiol 2014;14:44.
78. Chiao SS, Colquhoun DA, Naik BI, et al. Changing default ventilator settings on anesthesia machines improves adherence to lung-protective ventilation measures. Anesth Analg 2018;126(4):1219–22.
79. Parks DA, Short RT, McArdle PJ, et al. Improving adherence to intraoperative lung-protective ventilation strategies using near real-time feedback and individualized electronic reporting. Anesth Analg 2021;132(5):1438–49.
80. Miskovic A, Lumb AB. Postoperative pulmonary complications. Br J Anaesth 2017;118(3):317–34.
81. O'Gara B, Talmor D. Perioperative lung protective ventilation. BMJ 2018;362:k3030.
82. investigators LV. Epidemiology, practice of ventilation and outcome for patients at increased risk of postoperative pulmonary complications: LAS VEGAS - an observational study in 29 countries. Eur J Anaesthesiol 2017;34(8):492–507.
83. Canet J, Gallart L, Gomar C, et al. Prediction of postoperative pulmonary complications in a population-based surgical cohort. Anesthesiology 2010;113(6):1338–50.
84. Gajic O, Dabbagh O, Park PK, et al. Early identification of patients at risk of acute lung injury: evaluation of lung injury prediction score in a multicenter cohort study. Am J Respir Crit Care Med 2011;183(4):462–70.
85. Levitt JE, Calfee CS, Goldstein BA, et al. Early acute lung injury: criteria for identifying lung injury prior to the need for positive pressure ventilation. Crit Care Med 2013;41(8):1929–37.
86. Kornas RL, Owyang CG, Sakles JC, et al, Committee SfAMsSP. Evaluation and Management of the Physiologically Difficult Airway: Consensus Recommendations From Society for Airway Management. Anesth Analg 2021;132(2):395–405.
87. Reitz KM, Kennedy J, Li SR, et al. Association Between Time to Source Control in Sepsis and 90-Day Mortality. JAMA Surg 2022. https://doi.org/10.1001/jamasurg.2022.2761.
88. Jimenez MF, Marshall JC, Forum IS. Source control in the management of sepsis. Intensive Care Med 2001;27(Suppl 1):S49–62.
89. Maccagnan Pinheiro Besen BA, Tomazini BM, Pontes Azevedo LC. Mechanical ventilation in septic shock. Curr Opin Anaesthesiol 2021;34(2):107–12.
90. Evans L, Rhodes A, Alhazzani W, et al. Surviving sepsis campaign: international guidelines for management of sepsis and septic shock 2021. Crit Care Med 2021;49(11):e1063–143.
91. Fan E, Brodie D, Slutsky AS. Acute respiratory distress syndrome: advances in diagnosis and treatment. JAMA 2018;319(7):698–710.
92. Munshi L, Del Sorbo L, Adhikari NKJ, et al. Prone position for acute respiratory distress syndrome. a systematic review and meta-analysis. Ann Am Thorac Soc 2017;14(Supplement_4):S280–8.
93. Alhazzani W, Belley-Cote E, Møller MH, et al. Neuromuscular blockade in patients with ARDS: a rapid practice guideline. Intensive Care Med 2020;46(11):1977–86.
94. Kiss T, Wittenstein J, Becker C, et al. Protective ventilation with high versus low positive end-expiratory pressure during one-lung ventilation for thoracic surgery (PROTHOR): study protocol for a randomized controlled trial. Trials 2019;20(1):213.
95. Carramiñana A, Ferrando C, Unzueta MC, et al. Rationale and Study Design for an Individualized Perioperative Open Lung Ventilatory Strategy in Patients on

One-Lung Ventilation (iPROVE-OLV). J Cardiothorac Vasc Anesth 2019;33(9):2492–502.
96. Bluth T, Serpa Neto A, Schultz MJ, et al. Effect of intraoperative high positive end-expiratory pressure (PEEP) with recruitment maneuvers vs low PEEP on postoperative pulmonary complications in obese patients: a randomized clinical trial. JAMA 2019;321(23):2292–305.
97. Simon P, Girrbach F, Petroff D, et al. Individualized versus fixed positive end-expiratory pressure for intraoperative mechanical ventilation in obese patients: a secondary analysis. Anesthesiology 2021;134(6):887–900.