Transpulmonary pressure monitoring during mechanical ventilation: a bench-to-bedside review

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Abstract

Different ventilation strategies have been suggested in the past in patients with acute respiratory distress syndrome (ARDS). Airway pressure monitoring alone is inadequate to assure optimal ventilatory support in ARDS patients. The assessment of transpulmonary pressure (P\textsubscript{TP}) can help clinicians to tailor mechanical ventilation to the individual patient needs. Transpulmonary pressure monitoring, defined as airway pressure (P\textsubscript{aw}) minus intrathoracic pressure (ITP), provides essential information about chest wall mechanics and its effects on the respiratory system and lung mechanics. The positioning of an esophageal catheter is required to measure the esophageal pressure (P\textsubscript{eso}), which is clinically used as a surrogate for ITP or pleural pressure (P\textsubscript{pl}), and calculates the transpulmonary pressure. The benefits of such a ventilation approach are avoiding excessive lung stress and individualizing the positive end-expiratory pressure (PEEP) setting. The aim is to prevent over-distention of alveoli and the cyclic recruitment/derecruitment or shear stress of lung parenchyma, mechanisms associated with ventilator-induced lung injury (VILI). Knowledge of the real lung distending pressure, i.e. the transpulmonary pressure, has shown to be useful in both controlled and assisted mechanical ventilation. In the latter ventilator modes, P\textsubscript{eso} measurement allows one to assess a patient’s respiratory effort, patient-ventilator asynchrony, intrinsic PEEP and the calculation of work of breathing. Conditions that have an impact on P\textsubscript{eso}, such as abdominal hypertension, will also be discussed briefly.

Key words: abdominal pressure, esophageal pressure, transpulmonary pressure, work of breathing, mechanical ventilation

Mechanical ventilation (MV) is a life-saving supportive treatment in patients with Acute Respiratory Distress Syndrome (ARDS). The correct management of the ventilator setting is an essential aspect in the care of these patients as MV itself can also cause significant lung damage, a process known as Ventilator-Induced Lung Injury (VILI) [1, 2]. Two main mechanisms may injure the lung during MV: firstly, the excessive distention of the alveolar wall, due to dangerously high inspiratory pressures and volumes (respectively identified by lung stress and strain); secondly, the recurring intra-tidal opening and closing of lung units whose shear stress is caused by the cyclic recruitment of collapsed tissue, probably as consequence of inadequate positive end-expiratory pressure (PEEP) levels (defined atelectrauma) [3–5].

Numerous clinical studies have evaluated different ventilator strategies aiming to minimize VILI in ARDS patients. A key study, performed by the ARDS Network, showed that a lung protective ventilation strategy, using lower tidal volumes (V\textsubscript{t}) of 6 mL kg\textsuperscript{-1} of ideal body weight (IBW) and limiting plateau pressure (P\textsubscript{plat}) to less than 30 cmH\textsubscript{2}O, is associated with improvement in survival [6]. This strategy reduced the risk of VILI through limiting lung stress and/or overdistension. Although the use of lung protective ventilation is currently the standard of care, P\textsubscript{plat} and V\textsubscript{t} have been shown to be an inadequate substitute in order to assess lung stress and strain, while the suggested limits may not be safe for all ARDS patients [4, 7]. Even though three subsequent randomized controlled clinical trials evaluated the effects of higher versus lower PEEP, no standardized protocol has
proved to improve survival in a mixed population of ARDS patients [8–10]. The PEEP level should be set to maximize the amount of recruitable lung tissue and prevent the cyclic intra-tidal recruitment/derecruitment, while avoiding overdistension of already open lung units. However, ARDS is a heterogeneous disease and patients widely differ in the amount of edema, atelectasis, loss of lung volume and lung consolidation presented [11, 12]. Although the recently issued Berlin definition is a good step forward to classify this heterogeneity, it is far from perfect, as it does not include quantification for extravascular lung water (EVLWI) and pulmonary vascular permeability index (PVPI) as suggested by others [13, 14]. Lung recruitability is an essential parameter when selecting PEEP and the large clinical trials failed to identify any benefit in survival probably because this important factor was ignored. This hypothesis is supported by the results of two meta-analysis reports showing that higher PEEP may be beneficial in sicker patients who are characterized by a greater amount of lung edema and better lung recruitability [15, 16]. This may especially be the case in patients with secondary ARDS related to an abdominal catastrophe, with capillary leak, fluid overload and intra-abdominal hypertension (IAH) [17–19]. IAH is defined as a sustained increase in intra-abdominal pressure (IAP) above 12 mm Hg. Fluid overload is not only a major cause of second and third space fluid sequestration leading to IAH but the edema of the abdominal and chest wall will result in a decrease in compliance of both the abdominal and thoracic compartment [20]. Therefore, the same PEEP level may cause overdistension in some patients or promote alveolar recruitment of collapsed tissue in others, based on the patient’s individual characteristics.

The traditional management of MV based on airway pressure monitoring limits one’s possibility to tailor the ventilator setting to the individual patient. Numerous pathophysiological events have a dramatic impact on respiratory mechanics in ARDS, such as: altered chest wall (fluid overload), increased IAP (capillary leak, fluid overload), amount of lung edema (increased EVLWI and PVPI) and collapse, distribution and asymmetry of lung disease (primary versus secondary ARDS), etc. Correct understanding of the overall influence of these factors on the respiratory system is fundamental in order to individualize effective and safe MV in more complex patients.

In recent years, the assessment of transpulmonary pressure (P_{TP}) is increasingly recommended to guide mechanical ventilation as it is a bedside tool that may help clinicians to improve gas exchange while avoiding lung injury in ARDS patient [21].

In this concise review, we will focus on the physiological rationale, measurement techniques and conditions that may influence esophageal pressure (P_{eso}) and the potential clinical applications of transpulmonary pressure (P_{TP}) monitoring.

**TRANSPULMONARY PRESSURE**

**DEFINITION**

Transpulmonary pressure (P_{TP}) is the real distending force of the lung parenchyma and it is calculated as the difference between the airway pressure (P_{aw}) and the pleural pressure (P_{pl}). The air moves across the respiratory system according to a pressure gradient between the alveoli and the environment.

\[
P_{TP} = P_{aw} - P_{pl}
\]

This pressure gradient can be negative as during spontaneous breathing, when the respiratory muscles generate negative pressure (P_{pl}) outside the lung to move air inside the respiratory system, or it can be positive provided by the ventilator at the airway opening during controlled mechanical ventilation, or a combination of the two mechanisms during assisted mechanical ventilation.

The P_{aw} is often assumed to mirror the forces applied on the lung and used to monitor MV in clinical practice. This assumption is erroneous because P_{aw} is a measure of the resistive and elastic properties of the total respiratory system, whose behavior depends on the characteristics and interaction of its two major components: the lungs and the chest wall. Consequently, the airway driving pressure acts on two structures placed in series and the change in pleural and transpulmonary pressures is the result of the ratio between their own mechanical properties (Fig. 1). Under static conditions (i.e., no airflow), elastance describes the elastic properties of the respiratory system and is defined as the pressure required to inflate 1 liter above its resting position [22]. As elastance of the respiratory system is usually increased in ARDS, accordingly we can only predict lung behavior if chest wall elastance remains normal. Unfortunately, chest wall alterations are common in ARDS patients and cannot be easily predicted [4, 12, 22–24]. Obesity, increased IAP, chest wall deformities, resuscitation with large fluid volumes, pleural effusion and other conditions, all increase chest wall elastance [25–27]. A stiffer chest wall entails higher pleural pressures because greater part of the driving pressure is required to move the chest wall. The consequence is that the same P_{aw} can generate dramatically different transpulmonary pressures and pleural pressures depending on the chest wall properties.

Different models have been proposed to calculate the transpulmonary pressure during MV (Table 1). All these strategies estimate P_{TP} through the measurement of P_{aw} and esophageal pressure (P_{eso}), which is the only clinically available surrogate of P_{pl}. The rationale and limitations of P_{eso} measurement will be discussed in depth in the following section.
ELASTANCE-DERIVED MEASUREMENT

The elastance-derived transpulmonary pressure method, originally described byGattinoni et al., calculates the end-inspiratory $P_{tp}$ and $P_{tp}$ through the ratio between the chest wall and lung elastance, respectively, to the respiratory system elastance [22]. In mathematical terms (with $E_{cw}$ respiratory system elastance, $E_L$ lung elastance and $E_{cw}$ chest wall elastance):

$$P_{aw} = P_{tp} + P_{pl}$$

and

$$E_{aw} = E_L + E_{cw}$$

Following this, the reciprocal parts of $P_{aw}$ spent to move outward the chest wall and to inflate the lungs can be calculated as following:

$$P_{tp} = P_{aw} \times E_L/ E_{aw}$$

and

$$P_{pl} = P_{aw} \times E_{cw}/ E_{aw}$$
This method is based on two assumptions. Firstly, as elastance is calculated using the change in $P_{aw}$ and $P_{pl}$ due to tidal volume, their variations must be linear during tidal volume inflation and PEEP. However, $E_l$ depends on lung volumes and may not be linear at the extremes of the pressure-volume curve. Secondly, elastance-derived $P_{TP}$ must be zero when $P_{aw}$ is zero, for mathematical reasons, even if this does not mean that the absolute value of $P_{TP}$ and $P_{pl}$ are equal to zero.

**RELEASE-DERIVED MEASUREMENT**

The second method described in the literature estimates end-inspiratory and end-expiratory $P_{TP}$ as the change in $P_{aw}$ and $P_{pl}$ due to both tidal volume ventilation and PEEP. Transpulmonary pressure is computed as the difference between $P_{aw}$ and $P_{pl}$ from end-inspiratory to atmospheric pressure or from PEEP to atmospheric pressure, respectively (Fig. 2). This technique has been defined as release-derived transpulmonary pressure [4, 22].
\[ P_{\text{TP}} (\text{at end-inspiration}) = P_{\text{aw}} (\text{at end-inspiration}) - P_{\text{es}} (\text{at atmospheric pressure}) - P_{\text{es}} (\text{at end-inspiration}) = P_{\text{aw}} - P_{\text{es}} (\text{at PEEP}) - P_{\text{es}} (\text{at atmospheric pressure}) \]

**DIRECT MEASUREMENT**

Finally, Talmor et al. validated the directly-measured end-expiratory \( P_{\text{TP}} \) [28].

\[ P_{\text{TP}} (\text{at end-expiration}) = P_{\text{aw}} (\text{at PEEP}) - P_{\text{es}} (\text{at PEEP}) \]

In an observational study, the authors computed end-expiratory \( P_{\text{TP}} \) as the absolute difference between PEEP and \( P_{\text{es}} \). Esophageal pressure averaged 17.5 ± 5.7 cm H\(_2\)O while the absolute \( P_{\text{TP}} \) was 1.5 ± 6.3 cm H\(_2\)O at end-expiration [29]. Interestingly, a significant number of patients showed a negative end-expiratory \( P_{\text{TP}} \) which suggested the presence of lung regions at risk of intra-tidal opening/closing and collapse. The negative sign of \( P_{\text{TP}} \) is a mathematical consequence of this method and it may be due to proximal airway closure during exhalation, alveolar flooding or related to enhanced regional \( P_{\text{pl}} \) variations in edematous lungs. However, \( E_{\text{cw}} \) was not correlated with the end-expiratory \( P_{\text{es}} \) suggesting that the chest wall pressure-volume curve was independent from the relative point on the pressure axis [30].

The common requirement of all \( P_{\text{TP}} \) measurement techniques, as discussed above, is the need for a reliable estimate of \( P_{\text{es}} \) which can be clinically estimated through the measurement of \( P_{\text{es}} \).

**ESOPHAGEAL PRESSURE**

**ESOPHAGEAL PRESSURE MEASUREMENT**

Despite the pivotal importance of \( P_{\text{es}} \) to evaluate lung stress and inflation during MV, it is difficult if not impossible to measure in clinical practice. The only available bedside surrogate of \( P_{\text{pl}} \) is esophageal pressure (\( P_{\text{es}} \)). Esophageal pressure has been proposed as a substitute of \( P_{\text{pl}} \) for the first time more than 60 years ago, although its clinical role is still marginal nowadays. Two reasons limit its routine use in ARDS patients: firstly, the expertise required for catheter positioning and accurate measurement and secondly, the correct interpretation of the results for clinical implementation. A study group, named PLeUrpressure working Group (PLUG), recently came together to promote the use of \( P_{\text{es}} \) in critically ill patients [21].

Esophageal pressure can be measured through a catheter with an air-filled balloon at the distal end; the signal is then transmitted to a pressure transducer at the proximal end for measurement (Fig. 3). A thin polyethylene tube with a standard 10-cm long balloon at the distal end essentially constitutes the catheters. The balloon covers multiple holes that transmit the changes in pressure to the transducer at the proximal end of the tube. The major advantages of this technique are that it is minimally invasive and feasible at the bedside. There are different types of esophageal catheters available on the market, each one characterized by different length, diameter, and compliance and filling volume of the balloon. These characteristics influence the measurement and must always be taken into account to ensure an accurate estimate of \( P_{\text{ps}} \). The volume of air instilled into the balloon is typical for each catheter type. Too low instillation volumes cause \( P_{\text{es}} \) to be underestimated, while overfilling will stretch the balloon and increase the internal balloon pressure leading to overestimation of \( P_{\text{es}} \) [31]. Newer catheters (Fig. 3) combine the balloon with a regular nasogastric tube that can be used for enteral feeding, enabling longer monitoring of \( P_{\text{es}} \) [32]. On the other hand, the presence of a standard nasogastric tube does not impair the measurement of \( P_{\text{es}} \) via a balloon tipped catheter [33].

The standard positioning technique includes different phases that support correct placement. The catheter is inserted through the nostril or the mouth (according to patient’s need) and advanced deflated into the stomach. Now the balloon is inflated and its position inside the stomach is confirmed by the presence of positive pressure increases during inspiration, if the patient is spontaneously breathing. This intragastric pressure measurement closely reflects the IAP [34]. Subsequently the balloon is withdrawn until the \( P_{\text{es}} \) variation becomes negative during inspiration, marking the transition into the thorax. This phase is not possible during passive MV, a circumstance in which the catheter retraction is mainly guided by the appearance of heart artifacts and a change in the absolute values of the \( P_{\text{es}} \) curve as it passes the gastro-esophageal junction. The catheter is withdrawn a further 10 cm to fit into the lower third of the esophagus, right below the heart (the typical distance from the nostril is 35–45 cm in adults) [35].

The occlusion test, first described by Baydur et al., is traditionally performed to validate the correct positioning of the catheter [36]. The occlusion test consists of measuring the ratio of \( P_{\text{es}} \) and \( P_{\text{aw}} \) change while the patient makes respiratory efforts against a closed airway. Because there is no change in volume, the transpulmonary pressure is constant and, thus, \( P_{\text{es}} \) and \( P_{\text{aw}} \) should change equally and simultaneously. If the ratio between the change in \( P_{\text{es}} \) and \( P_{\text{aw}} \) is between 0.8 and 1.2, the catheter provides a reliable estimate of \( P_{\text{ps}} \). In sedated and mechanically ventilated patients, this method was modified by applying external manual compressions on the thorax [37]. If the occlusion test is not satisfactory, first the filling volume of the catheter should be checked to rule out a potential under-filling error, and then the positioning should be repeated until correctly placed.
Other techniques have been proposed in the literature, such as: fluid-filled catheters and probes with pressure sensors in the tip, or the direct recording of the pleural pressure [38, 39]. As these catheter types have not yet been clinically validated, their use is less standardized than the air-filled catheters [38]. Instead, direct recording is risky and inadvisable in clinical practice because it requires a hole through the chest wall down to the pleural space [39].

Recently, moreover, a catheter with two balloons has been clinically validated, that allows simultaneous and continuous P_{eso} and IAP pressure measurement in awake or ventilated patients [32]. This allows one to calculate the transdiaphragmatic pressure gradient which may also be related to work of breathing, especially in COPD patients with use of accessory muscles (Fig. 3).

**INTERPRETING P_{ESO} MEASUREMENT**

The computation of P_{TP} depends upon the assumption that P_{eso} is a good estimation of P_{pl} and so that changes in P_{eso} mirror variations in P_{pl}. This assumption is largely based upon physiological studies in healthy subjects in the upright position [40, 41]. The esophagus is anatomically adjacent to the pleural space at its lower third and P_{pl} is simply transmitted through its wall because it can be considered a passive membrane. However, this relationship may not hold true in the supine position when the heart, the mediastinum, and the weight of the surrounding parenchyma compress the dependent lung or when lung disease causes regional differences in parenchyma aeration and perfusion [42, 43]. Even in healthy subjects, the supine position complicates the interpretation of P_{eso} measurements. Moreover, the supine position causes a decrease in lung volumes, and a greater increase in P_{eso} compared to similar volumes in the upright position [42].

Pleural pressure in a normal subject is generally slightly negative at rest, *i.e.* at Functional Residual Capacity (FRC), as the lung tends to recoil at lower volumes than the respiratory system. In fact, the chest wall tends to move outward, preventing the lung from collapse and causing a negative P_{pl}. Moreover, P_{pl} is not evenly distributed along the pleural space but there is a gradient from the upper to the lower regions. In an upright subject, P_{pl} is higher (*i.e.*, becoming more negative) in the apical than in the basal regions. This pressure gradient is caused by the weight of the lung itself, the differences in lung and chest wall shapes, and the fact that the lung is partly supported by the rib cage and the diaphragm. This gradient is around 0.2 cm H_{2}O per cm of height in healthy subjects [40, 44]. This relationship holds also true in the supine position [45]. However, at very low lung volumes, irrespective of body positioning, P_{pl} may exceed atmospheric pressure (*i.e.*, becoming positive) in the dependent regions, as the elastic recoil of the lung is smaller at lower volumes and the dependent parenchyma tends to be compressed [46]. This event is even more relevant in ARDS patients, in which the wet and edematous lungs are heavier and the gravitational gradient in pleural pressure is steeper [45, 47]. This vertical gradient of P_{pl} is clinically significant as it determines a gradient of P_{TP} and, therefore, also of the lung ventilation. Because P_{eso} is measured at the lower third of the esophagus, it underestimates P_{pl} surrounding the dependent lung and overestimates the pleural pressure around the non-dependent regions. Moreover, in ARDS patients, the lung is inhomogeneous and inter-regional differences in density or elastance may not be detected by
PEEP measurements. In an experimental study, Pelosi et al. found that Peso more closely reproduced mid-lung pleural pressure in supine dogs. Despite the significant differences in the absolute values of Peso and PTP changes in Peso and Pplat were similar in response to increasing Paw, thus suggesting that the variation of Peso is a reasonable estimate of the variations of Pplat and that Peso and Pplat were correlated at mid-lung height [45].

The calculation of absolute end-expiratory PTP has raised concerns about its reliability, as numerous factors influence the absolute value of Peso such as: respiratory mechanics, lung volumes, distribution of the disease, IAP, fluid status, previous surgery, positioning, heaith and mediastinum weight and the properties of the balloon. Washko et al. studied the magnitude and variability of postural effects on Peso in 10 healthy subjects [48]. Average PTP was 7.0 cmH2O lower in the supine than in the upright positioning at FRC. The authors found that approximately 4.1 cm H2O, corresponding to the 58% of this difference, could be attributed to the decrease in lung volume associated with supine position. The remaining 2.9 cm H2O change was due to horizontal displacement of the pressure-volume curve. Moreover, PTP at FRC in the supine position was negative in 7 out of 10 subjects, on average −3.3 ± 3.2 cm H2O, and it was still negative after correcting the value for the weight of the mediastinum. A study in obese patients found similar results: Peso increased from 0.1 ± 2.3 cm H2O to 9.4 ± 3.9 cm H2O when changing from the upright to the supine position respectively [49]. This study showed how the influence of mediastinum and tissue on Peso was similar in obese and normal subjects. Increased IAP and reduced chest wall compliance seemed to cause the higher Peso values, both in the upright and supine positions [49, 50]. The small artifacts in Peso are advocated to be predictable and acceptable compared to PTP values in patients with ARDS; consequently, Peso may accurately reflect Pplat in critically ill patients, as well as in healthy subjects [51]. In conclusion, despite some authors having promoted the use of absolute Peso values, further data on critically ill patients are necessary. Especially in relation to IAP and the correlation between intragastric pressures and Peso in view of an average index of transmission between the abdominal and thoracic compartments of 50%, IAP or intragastric pressure may be a useful and more easily available surrogate parameter for Peso at the bedside. Talmor, and others, found a very good correlation between IAP and Peso [29, 52].

### TRANSPULMONARY PRESSURE TO GUIDE MECHANICAL VENTILATION IN ARDS

In sedated and paralyzed patients, MV is currently set according to Peso and tidal volume, following the ARDS Network protocol [6]. This protocol recommends to limit VT < 6 mL kg\(^{-1}\) IBW and Pplat < 30 cm H\(_2\)O in order to improve survival. The Pplat pressure threshold is derived from the evidence that during spontaneous breathing total lung capacity is around a Pplat of 25 cm H\(_2\)O. If the patient has normal chest wall elastance, it corresponds to a Pplat of 30 cm H\(_2\)O and an animal study showed that this resulted in little lung inflammation and thus the absence of VILI [2].

During recent decades, the role of PEEP has changed from improving gas oxygenation towards the prevention of VILI. The main goals of PEEP are to keep the lung recruited and open, as well as to avoid the cyclic intra-tidal opening/closing of alveolar units — thus, shear stress. Because Pplat and VT have been shown to be poor surrogates of stress and strain, PTP has been advocated as a better guide for safe mechanical ventilation [4, 21]. In fact, as already shown, Paw can be used as a surrogate for PTP only if Pplat changed within a small range, which is not the case in clinical practice [22].

Esophageal pressure measurement allows one to titrate lung protective ventilation, tailored to the patients’ needs, providing appropriate and safe PTP while avoiding derecruitment and atelectrauma. Despite this strong pathophysiological rationale, clinical studies evaluating the efficacy of PTP-guided mechanical ventilation are still lacking (Table 2).

In a landmark study, Talmor et al. showed that PEEP setting according to the end-expiratory PTP was useful in ARDS patients [28]. Sixty-one patients were randomized to the standard ARDS Network protocol or to an intervention group in which PEEP was increased until achieving a PTP between 0 and 10 cm H\(_2\)O at end-expiration. All patients were ventilated with a VT of 6 mL kg\(^{-1}\) IBW or lower if required to keep the end-inspiratory PTP < 25 cm H\(_2\)O. End-expiratory transpulmonary pressure was computed as Paw (i.e., PEEP) minus the absolute Peso value at end expiration, corrected for positioning artifacts: 

\[
P_{TP} = P_{aw} - (P_{eso} + \delta)
\]

Here, \(\delta\) represents the mediastinal chest wall compliance. Grasso et al. [29, 52] and Talmor et al. [28] showed that a PTP−1 protocol was associated with improved survival and reduced complications such as ARDS, acute respiratory distress syndrome, ARDS-like events, and other severe respiratory failure. However, accounting for the mediastinal chest wall compliance may improve these results. Indeed, Talmor et al. proposed a PTP−1 protocol (Table 2) which was compared to a standard PEEP protocol with a PTP of 10 cm H\(_2\)O in a randomized controlled trial (Table 2). ARDS patients were ventilated with a VT of 6 mL kg\(^{-1}\) IBW or lower if required to keep the end-inspiratory PTP < 25 cm H\(_2\)O. End-expiratory transpulmonary pressure was computed as Paw (i.e., PEEP) minus the absolute Peso value at end expiration, corrected for positioning artifacts: 

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### Table 2. Studies evaluating the clinical use of transpulmonary pressure monitoring to guide mechanical ventilation in ARDS patients

<table>
<thead>
<tr>
<th>Authors/year</th>
<th>Study design</th>
<th>Population</th>
<th>Intervention</th>
<th>Conclusions</th>
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<tr>
<td>Talmor et al. 2008 [28]</td>
<td>RCT</td>
<td>61 ARDS patients</td>
<td>PEEP is increased to target an end-expiratory PTP of 0-10 cm H(_2)O</td>
<td>PTP strategy improved oxygenation and respiratory system compliance</td>
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<tr>
<td>Grasso et al. 2012 [55]</td>
<td>Observational prospective</td>
<td>14 ARDS patients with refractory hypoxemia</td>
<td>PEEP is increased to titrate an end-inspiratory PTP of 25 cm H(_2)O</td>
<td>PTP strategy improved oxygenation and prevented ECMO institution</td>
</tr>
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</table>

**RCT** — randomized controlled trial; **ARDS** — Acute Respiratory Distress Syndrome; **PEEP** — positive end-expiratory pressure; **PTP** — transpulmonary pressure; **ECMO** — extra-corporeal membrane oxygenation
— 5 cm H₂O). Positive end-expiratory pressure was then increased until P_r was greater than zero, suggesting that no expiratory lung collapse was present. The P eso-guided group showed better oxygenation, with a ratio of partial oxygen tension to the inspiratory oxygen fraction (PaO₂/FiO₂) being 88 mm Hg higher than in the control group (P = 0.002), and better respiratory system compliance (P = 0.001). These effects were persistent over the entire follow-up time, at 24, 48, and 72 hours. The interventional group showed higher PEEP levels, without any hemodynamic complications, and the end-inspiratory P_r never exceeded the “safe” limit of 25 cm H₂O. Although clinical outcomes and mortality were similar in the two groups, the study was not powered for these endpoints. To further explore the benefits of P_r monitoring to guide PEEP setting, the same group designed a subsequent multicenter trial (EPIVent 2 – ClinicalTrials.gov # NCT01681225) [53]. Moderate and severe ARDS patients are randomized to the interventional group in which PEEP is set to maintain an end-expiratory P_r greater than 0 cm H₂O, or to the control group in which PEEP is set accordingly to the ARDS Network PEEP/FiO₂ table (Table 3). The duration of the follow up in this study was prolonged from 3 to 28 days, while the primary endpoint is a composite outcome of mortality and ventilator-free days.

However, Chiumello et al. [54] found that setting PEEP accordingly to the absolute P eso value did not correlate with patient’s lung recruitability or lung weight obtained via a thoracic computed tomography (CT scan) [54]. Moreover, the chosen PEEP level also did not correlate with the severity of the disease.

A different method, targeting an open-lung approach by monitoring the end-inspiratory transpulmonary pressure, was suggested in patients with refractory hypoxemia [55]. The authors used the elastance-derived strategy to compute the actual contribution of E_cw on the respiratory system and set a P_r of 25 cm H₂O with the purpose to optimize gas exchange and avoid extra-corporeal membrane oxygenation (ECMO). End-inspiratory P_r was calculated as P_plat – (P_plat x E_cw/R_t). If the value of end-inspiratory P_r was lower than the target, PEEP was increased until the upper physiological limit of 25 cm H₂O. Fourteen patients were enrolled: 7 subjects had a P_r of 27.2 ± 1.2 cm H₂O and underwnt ECMO, while in the other 7 patients P_r averaged 16.6 ± 2.9 cm H₂O. Increasing PEEP (from 17.9 ± 1.2 to 22.3 ± 1.4 cm H₂O, P = 0.0001) to reach a P_r of 25.3 ± 1.7 cm H₂O improved oxygenation and allowed patients to be treated with conventional ventilation.

In conclusion, both end-expiratory and end-inspiratory P_r are important in ARDS and must be set accordingly to the individual patient’s respiratory characteristics. Two recent studies compared the P_r computation methods proposed in the literature [56, 57], Gulati et al. compared the absolute value of P eso versus the elastance-derived P_r to target an end-inspiratory P_r of 26 cm H₂O. The P_r values with the two approaches were discordant and could differ from each other by more than 10 cm H₂O. Moreover, there was no significant correlation between the optimal PEEP levels recommended by the two methods, while the change in pressure even moved into the opposite direction in 33% of the patients [56]. Chiumello et al. showed similar results in 44 ARDS patients. End-expiratory P_r based on the absolute P eso value and on the release-derived method was: −8.0 ± 3.8 and 3.9 ± 0.9 cm H₂O at 5 cm H₂O of PEEP and −1.2 ± 3.2 and 10.6 ± 2.2 cm H₂O at 15 cm H₂O of PEEP, respectively, and did not correlate well. Absolute P eso value was not related to lung weight, lung recruitability, the amount of un-aerated lung tissue on the CT scan nor to hypoxemia and chest wall elastance. Instead, there was a good correlation between the end-inspiratory P_r calculated with the elastance-derived and the release-derived methods. The mean elastance- and release-derived P_r was 14.4 ± 3.7 and 14.4 ± 3.8 cm H₂O at 5 cmH₂O of PEEP and 21.8 ± 5.1 and 21.8 ± 4.9 cm H₂O at 15 cmH₂O of PEEP, respectively. The results of these studies may not be surprising when taking into account the different goals of the different methods. A pathophysiological rationale must always be kept in mind when choosing one approach instead of another. Targeting an inaccurate P_pl could be potentially dangerous as it may lead to over- or underinflation of the lung and thus could cause VILI. On the contrary, a small observational study found a good correlation between PEEP values selected through a decremental PEEP trial with the PEEP set to achieve a P_r greater than zero [58].

Finally, a recent paper has described the presence of reverse triggering in deeply sedated patients during controlled mechanical ventilation [59]. This phenomenon is caused by the diaphragmatic muscle contractions triggered by ventilator insufflations. Reverse triggering occurred during 12% to 100% of the total recording period during fully controlled mechanical ventilation. Consequently, in this

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<td>FiO₂</td>
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<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PEEP</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
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<td>20</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>

FiO₂ — inspiratory oxygen fraction; PEEP — positive end-expiratory pressure

Table 3. Oxygenation – PEEP table of the control group of the EPIVent 2 trial (ClinicalTrials.gov # NCT01681225) [53]
situation $P_{\text{plat}}$ may no longer reflect $P_{TP}$, while MV can unexpectedly increase the risk of VILI.

**TRANSPIRUAL PRESSURE DURING ASSISTED MECHANICAL VENTILATION**

Assisted mechanical ventilation refers to those types of ventilator support in which the patient does part of the total work of breathing (WOB). This means that, according to the equation of motion of the respiratory system, the pressure required to inflate the lungs is the sum of the pressure applied by the ventilator to the airway ($P_{aw}$) and the pressure generated by the respiratory muscles ($P_{mus}$). During triggered ventilation the active contraction of the respiratory muscles initiates the assisted breath and the generated pressure depends upon the respiratory drive and the strength of the respiratory muscles. The consequence is that $P_{\text{plat}}$ does not mirror $P_{TP}$ because the downward diaphragm movement causes a negative pleural pressure swing that must be added to the pressures provided by the ventilator. High spontaneous breathing efforts generate high negative pleural pressures, which can significantly increase the transpulmonary pressure despite a normal-appearing $P_{\text{plat}}$ [60]. This phenomenon can be dangerous because $P_{TP}$ is uncontrolled and the risk of VILI is present even if $P_{\text{plat}}$ is below the 30 cm H$_2$O limit.

The rationale for assisted mechanical ventilation is to decrease the patient’s respiratory effort while preventing the risk of muscular atrophy associated with controlled mechanical ventilation, the so-called ventilator-induced diaphragmatic dysfunction, because part of the WOB is still sustained by the respiratory muscles. Other benefits related to assisted respiratory support are as follows: the decrease in sedation requirements, improved patient-ventilator interaction, and the recruitment of basal diaphragmatic lung regions with a consequent gas exchange improvement.

During assisted mechanical ventilation, although a good interaction between the patient and the ventilator is essential to effectively reduce WOB, it is often difficult to assess relying only on the standard monitoring of $P_{aw}$ and tidal volume. Esophageal pressure measurement can assess the patient’s real respiratory effort, patient-ventilator asynchrony, intrinsic end-expiratory positive pressure (iPEEP) and can help with the calculation of WOB. Moreover, $P_{eso}$ could also help one to guide the clinical titration of the support level during assisted ventilation.

The computation of WOB generated by the respiratory muscles can help the clinician to accurately weigh the amount of effort performed by the patient during assisted mechanical ventilation. Work of breathing is defined as the integral of the pressure required producing a change in volume. It is usually described on the Campbell diagram, which graphically represents the relation between the changes of $P_{eso}$ and the volume of the respiratory system during a breath. Esophageal pressure, as a surrogate of $P_{eso}$, represents the effort generated by the respiratory muscles to move the chest wall, i.e. the patient’s contribution during assisted breathing. Consequently, the Campbell diagram and the measurement of $P_{eso}$ allow for the partitioning of WOB into its elastic, resistive, inspiratory, expiratory, lung, and chest wall (and abdominal) components. Comparing the difference between $P_{eso}$ during an active breath and the pressure-volume curve of the relaxed chest wall can separate the resistive and elastic work. Work of breathing calculation showed that significant respiratory effort often occurs during mechanical ventilation [61]. Such measurement is important to titrate the level of ventilator support, to assess the presence of asynchrony or evaluate the performance during a weaning trial. Indeed, work of breathing proved to be a useful marker to predict weaning failure. Monitoring the trend in $P_{eso}$ swings during a spontaneous breathing trial helped to discriminate between patients who failed versus those who succeeded in a trial [62]. The $P_{eso}$ trend was also more accurate in predicting weaning failure than the shallow breathing index (defined as respiratory rate divided by tidal volume).

In presence of intrinsic PEEP (iPEEP), the measurement of WOB can underestimate the real oxygen consumption of the respiratory muscles because of the effort necessary to overcome iPEEP and initiate the tidal volume. If iPEEP is shown on the $P_{eso}$ curve as a drop in $P_{eso}$ before air flow starts, then the pressure-time product (PTP) is a more reliable measurement of oxygen consumption. The PTP is the product of the time spent in muscle contraction during inspiration as a percent of the total respiratory cycle time and the pressure generated by the muscle during inspiratory contraction [35]. The PTP was shown to discriminate between patients who fail or pass a spontaneous breathing trial [63].

Asynchrony is a major problem during assisted mechanical ventilation and is frequently clinically underestimated, which is associated with increased length of ventilation, ICU and hospital stay and mortality [64, 65]. Asynchrony derives from the mismatch between patient’s respiratory drive and one or more ventilator variables controlling the breathing pattern: trigger, flow or cycle. Although very common, asynchrony may be difficult to detect and interpret without an esophageal catheter or electromyography of the diaphragm to characterize the activity of the respiratory muscles [66, 67].

**CONCLUSIONS**

Transpulmonary pressure is an essential measurement in order to tailor mechanical ventilation to the individual patient’s needs. The benefits of $P_{TP}$ monitoring are relevant for both controlled and assisted mechanical ventilation. In ARDS patients it can help to optimize PEEP and driving
pressure, while avoiding further lung injury (VILI). During assisted mechanical ventilation, although the precise quantitative assessment of respiratory muscle activity needs calculation, the inspiratory effort can be straightforwardly observed through the esophageal pressure swings, a clinical evaluation easy to perform at the bedside. However more clinical studies are needed to establish the definite role of $P_{eso}$, $IAP$, and $P_{tp}$ at the bedside.

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