Esophageal Pressure Measurement: A Primer

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Summary

Over the last decade, the literature exploring clinical applications for esophageal manometry in critically ill patients has increased. New mechanical ventilators and bedside monitors allow measurement of esophageal pressures easily at the bedside. The bedside clinician can now evaluate the magnitude and timing of esophageal pressure swings to evaluate respiratory muscle activity and transpulmonary pressures. The respiratory therapist has all the tools to perform these measurements to optimize mechanical ventilation delivery. However, as with any measurement, technique, fidelity, and accuracy are paramount. This primer highlights key knowledge necessary to perform measurements and highlights areas of both uncertainty and ongoing development. Key words: esophageal pressure measurement; mechanical ventilation; PEEP; lung-protective ventilation; respiratory system driving pressure; transpulmonary driving pressure. [Respir Care 0;0(0):1–C15. © 2023 Daedalus Enterprises]
Introduction

Since the 1960s, respiratory therapists (RTs) have adapted their role as caregivers while technology and practice evolved. The evolution in ventilator technology provides tools previously only available for research; one example is esophageal pressure (P_{es}) monitoring. Although P_{es} measurement has been used for decades, it is only now that it is easily available at the bedside. The availability is both a benefit and a curse. It is a benefit because it is easily available and may provide useful information and a curse because, as with any pressure measurements, knowledge of both technique and physiology is essential; when these are lacking, errors occur.

P_{es} measurement perfectly aligns with the RT skills. The RT already possesses knowledge of the basic physiology related to transpulmonary pressures (P_{TP}), patient-ventilator synchrony, and the work of breathing. However, with this knowledge comes important responsibilities. Although evidence suggests some areas where P_{es} monitoring might be useful, we must be aware that currently there is no evidence that it improves outcomes. This brings back memories of lessons learned with pulmonary artery catheters (PACs), where technology was available earlier than evidence and was applied indiscriminately and with poor technique. Thus, we are responsible for using P_{es} monitoring with a sound physiological understanding, clear indications, protocolized and standardized practices, and following quality-assurance practices. Finally, we must continue to generate evidence to define for whom P_{es} measurement is needed and beneficial.

Although extensive reviews on this topic have been previously published, this primer aims to synthesize the basic knowledge needed to perform P_{es} measurements in a single document.

Physiology

The esophagus travels through the mediastinum and becomes adjacent to the pleural space (Fig. 1). The contiguity of the esophagus with the pleura allows the measurement of the pressure inside the esophagus as a surrogate for pleural space pressure measurement. Although it requires the placement of an esophageal catheter, it is easier and safer than a pleural tube. The validity and challenges of P_{es} as a surrogate of pleural pressure (P_{pl}) (Fig. 2) have been described in several studies. We will discuss below what P_{es} reflects and what it does not. The literature contains different terms and symbols for respiratory system measurements and calculations. Unfortunately, this has led to confusion. Thus, we created Tables 1–3 following a standardized notation published in this Journal, which contains the terms and the calculations distilled to the bedside level.

Pleural Pressure

Any particular P_{pl} measurement does not represent a homogeneous pressure throughout the pleural space. Instead, P_{pl} measurements vary according to the gravitational gradient (ie, ventral vs dorsal if supine or apical and basal if standing), lung weight, and regional lung inhomogeneities. For example, the vertical pleural gradient has been shown to increase by 1.8 times in the presence of lung injury due to an increase in lung weight. This is an important consideration because assuming P_{pl} measurements are the same at different points on the pleural surface may lead to errors in calculations, clinical interpretations of data, and therapy applications. See Figure 3 for P_{pl} gradients.

Transmural Pressures

A key concept in physiology is transmural pressure, the pressure difference across a structure. The transmural pressure is the stress the structure sees and, in the case of the alveoli, a proposed determinant of lung injury. The transmural pressure is obtained by subtracting the pressure inside the structure minus the pressure outside (a simple mnemonic is Pin minus Pout). Figure 2 demonstrates the concept of transmural pressure. The simplistic interpretation is that if the pressure outside a flexible structure is higher than inside the structure collapses, and if vice versa, the pressure inside is higher than outside the structure distends. This explains alveolar collapse, as well as vascular collapse.

The topic of pressure gradients and what they are called are a common source of confusion in the literature (Tables 1 and 2). For example, 2 commonly confused terms are transalveolar pressure (P_{TA}) and P_{TP}. P_{TA} is the difference between the alveolar pressure (P_{A}) and P_{pl}. P_{TP} is the pressure difference across the larger structure of the airways and lungs, calculated as the pressure at the airway opening (P_{AG}) minus P_{pl}. The legacy symbol for P_{TP} has been P_{l}, but this obscures the fact that P_{TP} is a difference in pressure between 2 points in space, whereas P_{L} seems to indicate the pressure at one point in space (ie, P_{L}).
Fig. 1. Relationship of the esophagus with the pleural space and airway. Representative computed tomography of the chest of a patient with an orogastric tube. Panel A and B: upper and mid thorax; note the relationship of the trachea, the esophagus, and the pleural space. Panel C: lower thorax; notice the relationship of the heart with the esophagus. An esophageal catheter placed too high will transmit airway pressures and too low the heart will transmit large cardiac oscillations.

Transmural pressure

\[ P_{in} - P_{out} = P_{across} \]

Trans-alveolar pressure difference

\[ P_A - P_{pl} = P_{TA} \]

Trans-pulmonary pressure difference

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

In static conditions  \( P_{TP} \approx P_{TA} \)

Fig. 2. Diagram of the respiratory system with one-compartment lung and chest wall. The chest wall is subdivided into rib cage and diaphragmatic and abdominal wall components. The arrows labeled \( \Delta \) muscle pressure (\( \Delta P_{mus} \)) indicate the positive directions of the corresponding \( P_{mus} \) differences. The diagram shows the pressure difference formulas color coded to allow better understanding of the terms transalveolar and transpulmonary pressure difference. From reference 10. \( \Delta P_{mus} = \) muscle pressure difference; \( di = \) diaphragm; \( P_{AO} = \) pressure at the airway opening; \( P_A = \) alveolar pressure; \( P_{pl} = \) pressure in the intrapleural space; \( RC = \) rib cage; \( BS = \) body surface; \( ab = \) abdomen; \( P_{TA} = \) transalveolar pressure; \( P_{TP} = \) transpulmonary pressure.
Table 1. Glossary of Terms

<table>
<thead>
<tr>
<th>Terms</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esophageal pressure</td>
<td>P_{es}</td>
<td>Pressure measured by the esophageal catheter (a surrogate for P_{a})</td>
</tr>
<tr>
<td>Pleural pressure</td>
<td>P_{pl}</td>
<td>Pressure in the pleural space (we use P_{a} as a surrogate)</td>
</tr>
<tr>
<td>Alveolar pressure</td>
<td>P_{A}</td>
<td>Alveolar pressure, equivalent to P_{AO} when flow throughout the respiratory system is zero</td>
</tr>
<tr>
<td>Pressure at the airway opening</td>
<td>P_{AO}</td>
<td>The pressure at the airway opening is the result of the addition of the chest wall and lung pressures</td>
</tr>
<tr>
<td>Body surface pressure</td>
<td>P_{BS}</td>
<td>Pressure on the body surface, generally atmospheric pressure; zero reference for pressure sensors measuring gauge pressure</td>
</tr>
<tr>
<td>Muscle pressure</td>
<td>P_{mus}</td>
<td>Pressure generated by ventilatory muscles to drive active inspiration or expiration</td>
</tr>
<tr>
<td>Transpulmonary pressure</td>
<td>P_{TP}</td>
<td>Pressure across the pulmonary system (airways, lungs, and chest wall)</td>
</tr>
<tr>
<td>Trans–chest wall pressure</td>
<td>P_{TCW}</td>
<td>Pressure difference across the chest wall</td>
</tr>
<tr>
<td>Transalveolar pressure</td>
<td>P_{TA}</td>
<td>Pressure across alveolar wall, also termed elastic recoil of lung, P_{sil} (L)</td>
</tr>
<tr>
<td>End-expiratory pleural pressure</td>
<td>P_{pl EE}</td>
<td>Usually after an expiratory pause, but can be measured without it</td>
</tr>
<tr>
<td>End-inspiratory pleural pressure</td>
<td>P_{pl EI}</td>
<td>Usually after an inspiratory pause, but can be measured without it</td>
</tr>
</tbody>
</table>

**Partitioning Respiratory System Compliance**

The P_{AO} is the gauge pressure (ie, relative to atmospheric pressure) seen by the ventilator airway pressure (P_{AW}) sensor. It represents the pressure difference across the respiratory system, which includes the pressure due to flow resistance and the pressure due to elastic recoil of the lungs and chest wall. Ventilators are designed assuming that the respiratory system can be represented by a single-compartment model governed by the equation of motion. As a result, ventilator waveforms are graphical representations of the equation, and ventilators only calculate a single resistance and compliance to represent both lungs and the chest wall combined. Because P_{AO}, as measured by the ventilator, is relative to body surface pressure (P_{BS}) it is actually a pressure difference called trans–respiratory system pressure (P_{TR} = P_{AO} – P_{BS}). Figure 2 illustrates the transmural pressures. By knowing the P_{pl}, the pressure outside the lung (between the chest wall and the lung), we can partition the P_{TR} into the P_{TP} and trans–chest wall pressure (P_{TCW}). Supplementary appendix highlights the derivation of the equations (See related supplementary materials at http://www.rcjournal.com). Table 2 outlines the equations as they would be applied at the bedside.

**Patient Effort**

P_{es} can help identify the presence and magnitude of the patient’s respiratory effort. This has relevance in terms of patient-ventilator interactions (PVIs) and estimating the amount of ventilator assistance and may be essential to prevent diaphragm injury. Although P_{es} can be used to do detailed calculations on the work of breathing (the reader can learn more detail here), for the sake of this primer, we will focus on basic P_{es} assessments of patient effort.

The P_{es} waveform shows **inspiratory effort** as a deflection below baseline P_{es} (ie, negative-going pressure).Expiration is usually passive, but if there is an **expiratory effort**, it shows as a deflection above baseline (ie, positive-going pressure). For unassisted breathing, the amplitude of the P_{es} swing reflects the magnitude of ventilatory muscle activation. During mechanical ventilation, the P_{es} deflection during active inspiration may not go below baseline throughout the inspiratory effort because increase in P_{es} due to positive-pressure inflation by the ventilator offsets the negative-going P_{es} due to the patient’s inspiratory effort. This sometimes makes interpretations more challenging. The depth of the P_{es} drop, or swing, will vary according to several factors, such as lung compliance (C_{L}), resistance, abdominal pressure, lung volume, if the airway is occluded or not (Muller maneuver), presence of mechanical ventilation, and, of course, the ventilatory muscle function (strength). Thus, assessing these pressure swings must be considered in the patient’s overall condition and physiology.

**Patient-Ventilator Synchrony**

P_{es} monitoring also allows the evaluation of the patient’s effort timing in relation to the ventilator events (trigger and cycle). For most patients, examining ventilator flow and pressure waveforms is sufficient to detect the presence of ventilatory efforts; however, P_{es} allows us to see closer to the origin of the effort (ie, the brain). This can be especially useful when the ventilator waveforms are equivocal or to identify events more precisely such as early (reverse) trigger and failed trigger. Timing differences between the ventilator and patient can be measured when the airway and the P_{es} signals are recorded simultaneously. There is always a normal difference in timing between P_{es} and the ventilator events. This delay is expected due to the signal traveling through the airway to the sensor to activate the ventilator and to the intrinsic delay of the ventilator control circuit. Currently, there are no standard definitions for the timing differences to classify normal, late, or early trigger.
Table 2. Calculations

<table>
<thead>
<tr>
<th>Term</th>
<th>Formula</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transrespiratory system pressure</td>
<td>$P_{TR} = P_{AO} - P_{RS}$</td>
<td>Pressure across vascular wall, as an example here with the PAOP</td>
</tr>
<tr>
<td>Transpulmonary pressure</td>
<td>$P_{TP} = P_{AO} - P_{pl}$</td>
<td></td>
</tr>
<tr>
<td>Trans–chest wall pressure</td>
<td>$P_{TCW} = P_{pl} - P_{RS}$</td>
<td></td>
</tr>
<tr>
<td>Transvascular pressure</td>
<td>$P_{TV} = PAOP - P_{pl EE}$</td>
<td></td>
</tr>
<tr>
<td>Respiratory system compliance</td>
<td>$C_{RS} = V_T/(P_{pl} - P_{PEEPtot})$</td>
<td>Used to calculate the non-dependent $P_{pl}$ by the elastance method</td>
</tr>
<tr>
<td>Chest wall compliance</td>
<td>$C_{CW} = V_T/(P_{es EI} - P_{es EE})$</td>
<td>Used to calculate the non-dependent $P_{pl}$ by the elastance method</td>
</tr>
<tr>
<td>Lung compliance</td>
<td>$C_{L} = V_T[(P_{pl}) - (P_{es EI} - P_{es EE})]$</td>
<td>See text; does not correlate with actual $P_{pl}$ in ventral areas; preferred elastance method</td>
</tr>
<tr>
<td>Elastance</td>
<td>$E$ = 1/C</td>
<td>Used to calculate the dependent $P_{pl}$ and titrate PEEP</td>
</tr>
<tr>
<td>Respiratory system elastance</td>
<td>$E_{RS} = (P_{pl})/V_{T}$</td>
<td>See text; this method yields a $P_{es}$ closer to the $P_{pl}$ in the non-dependent lung regions</td>
</tr>
<tr>
<td>Chest wall elastance</td>
<td>$E_{CW} = (P_{es EI} - P_{es EE})/V_{T}$</td>
<td>Used to calculate the dependent $P_{es}$ and titrate PEEP</td>
</tr>
<tr>
<td>End-inspiratory transpulmonary pressure</td>
<td>$P_{TP EI} = P_{pl} - P_{es EI}$</td>
<td>No pause maneuvers; measure inspiratory values at lowest $P_{es}$</td>
</tr>
<tr>
<td>End-inspiratory transpulmonary pressure, elastance method</td>
<td>$P_{TP EI clas} = P_{pl} - P_{pl} \ ' (E_{cw}/E_{RS})$</td>
<td>Nadir refers to the lowest point in $P_{es}$ during spontaneous breaths</td>
</tr>
<tr>
<td>End-expiratory transpulmonary pressure</td>
<td>$P_{TP EE} = P_{pl} - P_{es EE}$</td>
<td></td>
</tr>
<tr>
<td>Transrespiratory DP</td>
<td>$P_{TR} = P_{pl} - P_{PEEPtot}$</td>
<td></td>
</tr>
<tr>
<td>Transpulmonary DP static</td>
<td>$\Delta P_{TP static} = (P_{pl}) - (P_{es EI} - P_{es EE})$</td>
<td></td>
</tr>
<tr>
<td>Transpulmonary DP dynamic</td>
<td>$\Delta P_{TP dyn} = (P_{peak} - P_{PEEP}) - (P_{es EE} - P_{es nadir})$</td>
<td></td>
</tr>
<tr>
<td>Esophageal swing (Pes swing)</td>
<td>$\Delta P_{es} = P_{es EE} - P_{es nadir}$</td>
<td></td>
</tr>
</tbody>
</table>

PAOP = pulmonary artery occlusion pressure

$V_T$ = tidal volume

$P_{pl}$ = plateau pressure

DP = driving pressure

Table 3. Esophageal Catheter Adverse Events and Contraindications

<table>
<thead>
<tr>
<th>Adverse Events</th>
<th>Contraindications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epistaxis</td>
<td>Severe coagulopathy (eg, thrombocytopения)*</td>
</tr>
<tr>
<td>Esophageal injury (eg, mucosal tear, perforation)</td>
<td>Esophageal injury (eg, perforation, recent banding)</td>
</tr>
<tr>
<td>Tracheal insertion or injury</td>
<td>Risk of worsening injury (eg, nasal fractures/surgery)</td>
</tr>
<tr>
<td>Pneumothorax</td>
<td>Recent base of skull surgery</td>
</tr>
</tbody>
</table>

* Coagulation thresholds for procedures are institution dependent.

or cycle events, so most assessments are visual rather than based on measurements.22

Another timing consideration to be able to do the assessments of synchrony is where in the $P_{es}$ waveform the breath starts and ends. The inspiratory effort reflected in the $P_{es}$ waveform is normally relatively irregular from breath to breath, but we usually consider it sinusoidal for simplicity. Different inspiratory and expiratory muscle activation patterns may yield various waveforms. This is relevant as we use the $P_{es}$ waveform to assess patient-ventilator synchrony. As the inspiratory muscles activate, a drop in $P_{es}$ follows, signaling the start of the breath. The muscles relax to initiate expiration soon after the peak inspiratory effort (the most negative $P_{es}$ deflection).

The $P_{es}$ can help detect asynchronies such as false or failed triggers. Negative deflection of the $P_{es}$ waveform in the absence of a ventilator-delivered breath is a manifestation of ventilatory muscle pressure ($P_{mus}$) failing to trigger the ventilator. The absence of negative $P_{es}$ deflections reflecting patient effort and the presence of patient-triggered ventilator breaths are consistent with a false trigger. Diagnosing these discordances requires clinical correlation, patient exam, review of ventilator waveforms, and occasionally doing end-expiratory (EE) pause maneuvers to define the interaction better.21

**Technical Considerations**

Placement of an esophageal balloon for measurement is relatively easy. The technique for insertion is the same as placing an orogastric/nasogastric tube for feeding. However, esophageal catheter placement has the risk of adverse events...
and has a few contraindications (Table 3). The risks are related to mechanical complications from the placement of the device, such as bleeding or perforation. The esophageal catheters can be placed for a single measurement or left in place to allow sequential measurements. When considering leaving a catheter in place for prolonged periods (eg, days), multifunction devices (eg, a feeding catheter with an esophageal manometry channel) may be preferred to minimize the number of devices in the airway and esophagus. Esophageal balloon catheters can be placed next to existing orogastric/nasogastric feeding tubes.

**Supplies**

A list of supplies would include the esophageal catheter set, tubing to connect to a pressure transducer, measurement monitor (standalone, bedside monitor, or ventilator), syringe, and lubrication. If the patient is awake, consider a topical anesthetic for nasal insertion.

**Catheter Insertion and Position**

The correct insertion depth is determined by measuring the length (with tape or the catheter) from the xiphoid, across the tip of the earlobe, to the tip of the nose. In addition, some catheters have a radiological marker or guidewire, allowing placement confirmation during a standard chest radiograph.

The patient is placed in a semi-recumbent position, and the lubricated device (with the balloon deflated) is inserted nasally or orally. Insertion should reach the stomach at approximately 60 cm. The presence of cough, ventilator alarms, or \( P_{es} \) waveforms like the \( P_{AOD} \) should raise concerns for tracheal penetration. Therefore, assessment of the \( P_{es} \) waveform is important during the placement as airway waveforms may become evident.

The balloon is then inflated to a prespecified volume (see below), and the catheter is withdrawn until a change in pressure from intra-abdominal to intrathoracic is observed or cardiac oscillations are visible. The large cardiac oscillations decrease as the catheter is withdrawn into position (Fig. 4). The catheter may be underinflated, kinked, or require further advancement if no oscillations exist. The goal is to reach an area consisting of the lower third of the esophagus where the pleural space is near the esophagus, and the weight of the heart is minimal. Once in place, an occlusion test and assessment of the balloon volume are performed.

**Inflation Volume and Calibration**

Currently, there are a variety of esophageal catheters available for clinical use. Because each has distinct characteristics, the clinician must review the manufacturer’s recommended balloon inflating volumes. This is particularly important as inflating volumes have been shown to alter results. Underinflation of the balloon leads to underestimation or \( P_{es} \), whereas overinflation causes overestimation.

When inflating the balloon, the team must follow steps to ensure the accuracy of the balloon volume (see Tables 4 and 5). There are methods to calibrate the \( P_{es} \) to deliver more accurate values such as using a standard correction factor, the relaxation volume, or the esophageal wall elastance. Overall, there are 2 common practices for inflating the balloon. The first inflates the balloon to a specific volume, within which the balloon performs well according to the manufacturer or prior research, without performing any calibration. This was the method used in the 2 largest \( P_{es} \) trials. The second common practice is to find the optimal balloon inflation volume, defined as the lowest volume that delivers the

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**Fig. 3.** Computed tomography of the chest highlighting the pleural pressure \( (P_{pl}) \) gradient and dependent and non-dependent areas of the lung. Line A demonstrates the \( P_{pl} \) at the non-dependent areas of the lung. Line B demonstrates the mid-lung \( P_{pl} \); note the orange circle is the esophagus and is the location where \( P_{pl} \) is being measured. Line C is the pressure at the dependent areas of the lung. The \( P_{pl} \) gradient is the difference in pressure from line A to C. The blue line outlines the pleura. The red line outlines the heart.
largest $P_{es}$ pressure change. After finding the $V_B^{best}$, then the $P_{es}$ is corrected for the pressure added from the esophageal wall. In a recent trial, the authors used a combination of these practices; the catheter is inflated to a predefined value, and if the occlusion test (see below) is not within range (0.8–1.2), then calibration of the balloon is performed, and the occlusion test is repeated. Table 5 outlines the steps for balloon inflation and how to correct for esophageal elastance.

Validating Measurements

The occlusion test is used to validate the $P_{es}$ readings. See Figure 5. The test compares the change in $P_{AW}$ ($\Delta P_{AO}$) and the change in $P_{es}$ ($\Delta P_{es}$) during an EE hold maneuver. If the patient is passive (no $P_{max}$), a slight compression on the chest wall will create positive intrathoracic pressure leading to a positive deflection of the $P_{es}$. If the patient has inspiratory efforts, the $P_{es}$ deflection will be negative. The $\Delta P_{es}/\Delta P_{AO}$ should be within 20% of each other, a ratio of 0.8–1.2. After placement, the guidewire (if present) should be removed and the catheter secured. A chest radiograph may be part of the protocol for proper safety and confirmation.

Recording Interface

The recording interface generally falls into one of 3 categories: the patient bedside hemodynamic monitor, mechanical ventilator, or standalone device. Patient bedside hemodynamic monitors are universally available and thus are an attractive option; however, teams must be aware that values are displayed in mm Hg (requiring conversion to cm H2O by multiplying by 1.36). In addition, there is no concurrent airway signal; thus, the evaluation of synchrony is not simple. Standalone devices also are available and use $P_{AW}$ and flow transducers, which connect at the Y-piece of the ventilator circuit. Finally, some mechanical ventilators have added $P_{es}$ capabilities in recent years; these allow displaying concurrent $P_{AO}$, $P_{es}$ signals, and calculated $P_{TP}$ waveforms.
Table 4. Esophageal Pressure Calibration and Validation Terms and Formulas

<table>
<thead>
<tr>
<th>Terms</th>
<th>Abbreviation or Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esophageal elastance</td>
<td>$E_{es}$</td>
<td>Describes the esophageal wall reaction to balloon filling</td>
</tr>
<tr>
<td>Esophageal balloon filling volume</td>
<td>$V_B$</td>
<td>Volume of gas used to inflate the esophageal balloon</td>
</tr>
<tr>
<td>Optimal (best) balloon filling</td>
<td>$V_{B;best}$</td>
<td>Within the $V_{B;min}$ to $V_{B;max}$ range, the smallest $V_B$ associated with the largest tidal $P_{es}$ swing</td>
</tr>
<tr>
<td>Minimum balloon volume</td>
<td>$V_{B;min}$</td>
<td>Smallest balloon volume that allows accurate measurements of EE $P_{pl}$ (smallest $V_B$ of the linear part of the esophagus balloon PV curve)</td>
</tr>
<tr>
<td>Maximum balloon volume</td>
<td>$V_{B;max}$</td>
<td>Largest balloon volume that does not cause overstretch of the balloon wall (largest $V_B$ of the linear part of the esophagus balloon PV curve)</td>
</tr>
<tr>
<td>Esophageal elastance</td>
<td>$E_{es}$</td>
<td>Slope of the linear part of the PV curve of the esophagus. Obtained by step inflation (or deflation) of esophageal balloon while recording the $P_{es;EE}$ and $V_B$</td>
</tr>
<tr>
<td>Esophageal wall pressure change</td>
<td>$\Delta P_{EW}$</td>
<td>Pressure generated by esophageal wall at the $V_{B;best}$</td>
</tr>
<tr>
<td>Calibrated $P_{es}$</td>
<td>$P_{es;cal} = P_{es} - \Delta P_{EW}$</td>
<td>Formula to calibrate $P_{es}$ by subtracting the esophageal wall pressure to approximate better the $P_{pl}$</td>
</tr>
<tr>
<td>Occlusion test</td>
<td>$\Delta P_{AO}/\Delta P_{es}$</td>
<td>Ratio obtained with an expiratory occlusion maneuver during effort or a gentle chest compression. Acceptable: 0.8–1.2</td>
</tr>
</tbody>
</table>

$P_{es}$ = esophageal pressure
$P_{pl}$ = pleural pressure
EE = end expiratory
PV = pressure-volume

Fig. 5. Occlusion test. Panel A demonstrates the pressure at the airway opening ($P_{AO}$) (red line) and esophageal pressure ($P_{es}$) (blue line) during an end-expiratory (EE) pause maneuver (occlusion) in a patient with inspiratory effort. Notice the overlap of pressures during inspiratory effort. The blue arrow is the $\Delta P_{es}$ and the red arrow the $\Delta P_{AO}$ used to calculate the ratio. Panel B demonstrates the $P_{AO}$ and $P_{es}$ in a patient without any effort and on mechanical ventilation. Between the mechanical breaths (*), an EE pause maneuver is performed along with gentle compressions of the chest. The blue arrow is the $\Delta P_{es}$ and the red arrow the $\Delta P_{AO}$ used to calculate the ratio. Adapted with permission from reference 4. $P_{es}$ = esophageal pressure; $P_{AO}$ = pressure at the airway opening.

There are solid-state, air- and fluid-filled balloons, and catheters without balloons. Comparisons in performance are few, as in clinical practice most monitoring systems use air-filled catheters. If using a bedside monitor to perform measurements, remember that this also uses air-filled transducers (as opposed to the saline filled used for hemodynamic monitoring).
Measurements and Calculations

Monitoring of $P_{es}$ may lead the team to implement management and ventilator settings changes. Thus, the accuracy and reliability of measurements are very clinically relevant. Although research has been ongoing for decades, several areas of controversy and uncertainty remain.4,5,37

**Table 5. Steps to Measure Esophageal Pressure**

**Balloon Inflation Step**
Before any inflation, remove all the air from the balloon and de-connect to ambient air for 2–3 s (if the patient is spontaneously breathing, ask active expiration while you de-connect).

**Placement**
1. Place $P_{es}$ catheter (usual depth 30–45 cm)
2. Inflate balloon to a standard volume or consider calibrating to optimal balloon volume (see below)
3. Perform occlusion test to ensure transduction of $P_{es}$ is valid (ratio 0.8–1.2)
4. Ensure patient steady state; some patients need sedation +/- paralysis
5. Be ready to freeze the screen on devices

**Calibration to esophageal balloon volume**
1. Define balloon nominal volume according to catheter32 (NutriVent = 8 mL, Cooper = 2.4 mL)
2. Inflate to nominal volume
3. Deflate in 0.5–1.0 mL steps (depending on size of catheter) and note the $P_{es}$ EE and $P_{es}$ swing
4. Detect the linear part of the $P_{es}$ EE VB curve and its limits ($V_{B_{min}}$ and $V_{B_{max}}$)
5. Detect $V_{B_{best}}$ (lowest $V_{B}$ with largest $P_{es}$ swing within $V_{B_{min}}$ and $V_{B_{max}}$)
6. Compute $E_{es}$: $E_{es} = (P_{es} at \ V_{B_{max}} - P_{es} at \ V_{B_{min}}) / (V_{B_{max}} - V_{B_{min}})$
7. Compute $PEW$: $PEW = (V_{B_{best}} - V_{B_{min}}) / E_{es}$
8. Compute calibrated $P_{es} cal = P_{es} - PEW$

**Example steps to deflate esophageal balloon to calibrate**
- NutriVent catheter (Sidam, Mirandola, Italy): 8, 7, 6, 5, 4, 3, 2, and 1 mL
- Cooper catheter (CooperSurgical, Trumbull, Connecticut): 2.4, 2.1, 1.8, 1.5, 1.2, 0.9, 0.6, and 0.3 mL

**Partitioning of respiratory system**
1. Perform EE pause and EI pause (3 s or to reach plateau)
2. Pause images on screen
3. Measure $P_{es}$ EE and $PEP_{tot}$ at same time points*
4. Measure $P_{es}$ EI and $P_{plut}$ at same time points*
5. Use elastance-based method to correct the EI $PTP$
   $PTP_{EE} = E_{es} / P_{ES}$
   $PTP_{EI elast} = (P_{plut} - P_{plut} / (E_{es}/E_R))$

**Titration of PEEP**
1. Adjust PEEP to achieve $PTP_{EE}$ of 0 ± 2
2. If persistent hypoxemia, increase PEEP; may want to follow trial table (reference 32)
3. Assess $PTP_{EI elast}$ to ensure within safe range

**Patient effort**
1. During spontaneous breathing ± mechanical ventilation
   $\Delta P_{es} = P_{es} EE - P_{es} nadir$

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**Esophageal Pressure Measurements**

Table 5 outlines the steps for measuring $P_{es}$. The best practice is to use a printout or static waveform (freeze it) on the monitor screen and then use digital cursors or rulers to perform the measurements. The $P_{es}$ waveform will show artifacts from cardiac oscillations; when present, the place...
to measure is where no cardiac oscillation artifact exists or in the middle of the peak and valley caused by the oscillation (Fig. 6). When calculating transmural pressure, the Pes and PAO should be measured at the same time point. Several measurements are done during end inspiration or end expiration with or without a pause maneuver. We aim to do some measurements when the patient is passive (no Pmus); in others, we assess inspiratory or expiratory effort. Positive (expiratory effort) or negative (inspiratory effort) Pes deflections during an end-inspiratory (EI) or expiratory pause are usually due to muscle effort. The presence of an upslope of the Pes waveform suggests the presence of expiratory muscle activity38 (Fig. 7). A bolus of sedation or paralysis eliminates artifacts when there is concern that the measurements are affected by respiratory muscle activity.

End-Expiratory Esophageal Pressure

Although a source of controversy, the latest evidence in lung injury is that the EE Pmus accurately reflects the Pmus for the mid and dependent lung (dorsal or basal).7 As discussed before, calibration can be performed to improve the accuracy of measurements. The PTP EE is used for titration of PEEP30,39 or correction of vascular pressures (for example, the pulmonary artery occlusion pressure).15 See the equations in Table 2.

End-Inspiratory Esophageal Pressure (Elastance-Based)

The EI pressure (plateau) during mechanical ventilation is a marker of potential ventilator-induced lung injury (VILI).13 Evidence and clinical practice suggest that the lung areas more prone to overdistention and high strain and stress are the non-dependent areas of the lung (apical or ventral for upright and supine positions, respectively).39 Studies on the Pplat gradient have demonstrated that measurements of Pmus correlate well with dependent lung areas but underestimate the non-dependent Pmus.4 One study demonstrated that using the measured Pmus EI will underestimate the Pplat in ventral areas. This is relevant if the clinician uses this to titrate tidal volume (VT), as the underestimation will lead to incorrectly thinking the patient is within safe thresholds. So correcting Pplat using the ratio of chest wall elastance to respiratory system elastance better approximates the Pmus in the non-dependent portions of the lung7 (see Tables 2 and 5). However, the elastance method requires more calculations; and so far, no recent study has used this method to titrate ventilation (the most recent ones have used measured PTP EI).29,30,32

Fig. 6. Site of measurements to evaluate the transpulmonary pressure (PTP). Top panel has the pressure at the airway opening (PAO), the middle panel the esophageal pressure (Pes) as a surrogate for pleural pressure. And the lower panel has the PTP. Asterisk highlights the cardiac oscillations. A: the end-expiratory (EE) PAO; B: the EE Pes; C: the EE PTP; D: the end-inspiratory (EI) PAO; E: the EI Pes; F: the EI PTP. Modified from reference 30. Reprinted with permission from reference 30. PAO = pressure at the airway opening; Pes = esophageal pressure; PTP = transpulmonary pressure.
Esophageal Pressure Swing

The $P_{es}$ swing is the drop in $P_{es}$ ($\Delta P_{es}$) from baseline ($P_{es\,EE}$) to the minimum pressure ($P_{es\,EI}$) that occurs during activation of the inspiratory muscles.\textsuperscript{16} The range is to be defined;\textsuperscript{32} one study defined an inspiratory $\Delta P_{es} < 7$ cm H$_2$O is consistent with low respiratory effort, whereas $\Delta P_{es} > 14$ cm H$_2$O suggests very high respiratory effort.\textsuperscript{16} A recent trial focused on keeping the $\Delta P_{es}$ at 3–8 cm H$_2$O to prevent disuse atrophy and overuse injury.\textsuperscript{32} The measurements are obtained during non-occluded breaths (not during an expiratory pause). The equation is represented in Table 2.

Static and Dynamic Transpulmonary Driving Pressure

The driving pressure (DP) $\Delta P$ uses static measures (plateau pressure [$P_{plat}$] and PEEP$_{tot}$) to scale the $V_T$ to the respiratory system compliance (see Table 2). This is recognized as a predictor of poor outcomes for patients with ARDS\textsuperscript{40} and is actively being explored as a target to titrate mechanical ventilation. Using $P_{es}$ along with $P_{AO}$ allows calculation of the transpulmonary DP ($\Delta P_{TP}$). These can be done during static conditions (no $P_{mus}$ and obtaining measurements during EI and expiratory pauses) or dynamic (during spontaneous breathing and obtaining measurements at the maximal esophageal swing).\textsuperscript{41}

The current understanding is that static measurements better reflect the stress of non-dependent lungs; the threshold is believed to be $\Delta P_{TP\,static} < 20$ cm H$_2$O. In contrast, the dynamic measurements may better represent the stress seen by the dependent lung. This is explained by the fact that P$_{pl}$ are not homogenous in ARDS, and in injured areas, it is not well transmitted to other lung areas. Thus, inspiratory effort leads to local higher P$_{pl}$, which causes gas in other lung areas to move to the injured dependent lung (pendelluft), causing tidal recruitment, overdistention, and higher $\Delta P_{TP}$ in the dependent injured lung.\textsuperscript{31} Measurement is done during spontaneous (assisted or unassisted) breathing; measurements are taken at maximum $P_{mus}$ (ie, lowest $P_{es}$).\textsuperscript{32,41} Thus, dynamic $\Delta P_{TP}$ is a current target to minimize lung injury during inspiratory effort. The thresholds are being determined, but some trials have aimed at dynamic $\Delta P_{TP} < 15$ cm H$_2$O.\textsuperscript{16,32} See Table 2 for the formulas.

Sources of Error

As with any pressure measurement, $P_{es}$ measurements are affected by sources of error. These include improper positioning of the catheter, high or low balloon volume inflation, dampening of the waveform, cardiac oscillations, esophageal contractions, esophageal pathology (strictures, mass), hiatal hernia, high abdominal pressures (Fig. 7), the posture of the patient, esophageal wall abnormalities, and asymmetric lung disease.\textsuperscript{8,42}

Clinical Applications

Esophageal catheters are diagnostic tools that require careful setup and interpretation; they do not improve clinical outcomes in and of themselves. Ultimately, the effect on outcomes will depend upon correctly using, interpreting, and implementing interventions to change ventilation strategies. Because of all these variables and disease-specific heterogeneity, it may be challenging to demonstrate the benefit of $P_{es}$ measurements in randomized controlled trials.\textsuperscript{1} However, studies demonstrated that implementing a standardized protocol to assess respiratory mechanics using $P_{es}$ was safe and
and chest wall compliance. This allows further titration of PEEP and VT while assessing the EI and EE PTP. The threshold for EI P$_{es}$ is < 20 cm H$_2$O; however, there has been no trial where VT PTP EI has been used to titrate the ventilator settings. Experience in patients with very severe ARDS from H1N1 who were being evaluated for extracorporeal membrane oxygenation (ECMO) demonstrated that the use of elastance-based P$_{TP}$ allowed adjustment of ventilator settings (PEEP to a maximum P$_{TP EI,_clin}$), avoiding ECMO, and maintaining standard mortality rates.\textsuperscript{45}

### Titrations of PEEP

Using P$_{es}$ as a surrogate for P$_{pl}$ in the dependent lung, one can titrate PEEP to maintain a neutral or positive P$_{TP EI}$ to keep alveoli open during expiration. The current understanding is that negative P$_{TP}$ leads to alveolar collapse, affecting lung mechanics and gas exchange and increasing the risk of lung injury. Current evidence suggests that aiming to P$_{TP EI}$ values close to 0 ± 2 cm H$_2$O may be related to better outcomes.\textsuperscript{46}

### Evaluation of Patient-Ventilator Interactions

When assessing PVIs, we use the ventilator waveforms to deduce the presence of P$_{mus}$.\textsuperscript{19,21} However, P$_{es}$ may allow a more precise evaluation of P$_{mus}$. It allows comparison of the timing of ventilator and muscle events and may be used to quantify inspiratory or expiratory effort (Fig. 8). To date, no trial has used P$_{es}$ monitoring for adjusting ventilator settings to improve patient-ventilator synchrony in a protocolized manner. However, several studies have demonstrated its benefit in determining and classifying the PVI discordance.\textsuperscript{16,19,20} Regarding effort, P$_{es}$ may allow the detection of ventilator overassistance and underassistance, although the thresholds and definitions are still to be defined.\textsuperscript{47} Current research focuses on patient self-inflicted lung injury, diaphragmatic dysfunction/atrophy, and safe levels of patient respiratory effort.\textsuperscript{7,32,48} As appropriate thresholds for under-assistance and overassistance are defined,\textsuperscript{16,17,49} physicians could use P$_{es}$ to titrate sedative and paralytic medications, prevent/minimize diaphragmatic atrophy and facilitate weaning, devise and study therapies targeted at improving diaphragmatic function, and more accurately identify those that are likely to fail extubation following a successful spontaneous breathing trial.

### Summary

Esophageal manometry is a valuable tool whose clinical applications have expanded over the past decades and will likely continue to do so. Expertise is required to place and interpret data provided by these catheters accurately. It is paramount for the RT and physician to work together to provide consistent practice when using this diagnostic tool.
The story of the PAC remains a guide of the perilous pathway—new monitoring technology has. The PAC routine indiscriminate use with no clear evidence of benefit and a signal for harm led to a “cultural” ban and de-adoption. Subsequent randomized controlled trials of PAC failed to show benefits. Yet in selected populations, and following specific protocols, the PAC may convey essential information that could benefit patients. This history should serve our teams as a blueprint to do better. We believe the Peso measurement generates valuable information. However, to avoid repeating history, we suggest that clinicians must guide by the following principles: (1) This is not a tool for every patient; the intervention should answer a specific clinical question; (2) follow standardized procedures as the measurements are dependent on a precise technique; (3) follow institutional or evidence-based protocols to define management based on results because this is essential to ensure consistent behaviors; and (4) network and publish institutional experience to help define further best indications, interventions, and implementation.

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