The Application of Esophageal Pressure Measurement in Patients with Respiratory Failure

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Abstract

This report summarizes current physiological and technical knowledge on esophageal pressure (Pes) measurements in patients receiving mechanical ventilation. The respiratory changes in Pes are representative of changes in pleural pressure. The difference between airway pressure (Paw) and Pes is a valid estimate of transpulmonary pressure. Pes helps determine what fraction of Paw is applied to overcome lung and chest wall elastance. Pes is usually measured via a catheter with an air-filled thin-walled latex balloon inserted nasally or orally. To validate Pes measurement, a dynamic occlusion test measures the ratio of change in Pes to change in Paw during inspiratory efforts against a closed airway. A ratio close to unity indicates that the system provides a valid measurement. Provided transpulmonary pressure is the lung-distending pressure, and that chest wall elastance may vary among individuals, a physiologically based ventilator strategy should take the transpulmonary pressure into account. For monitoring purposes, clinicians rely mostly on Paw and flow waveforms. However, these measurements may mask profound patient–ventilator asynchrony and do not allow respiratory muscle effort assessment. Pes also permits the measurement of transmural vascular pressures during both passive and active breathing. Pes measurements have enhanced our understanding of the pathophysiology of acute lung injury, patient–ventilator interaction, and weaning failure. The use of Pes for positive end-expiratory pressure titration may help improve oxygenation and compliance. Pes measurements make it feasible to individualize the level of muscle effort during mechanical ventilation and weaning. The time is now right to apply the knowledge obtained with Pes to improve the management of critically ill and ventilator-dependent patients.

Keywords: pleural pressure; respiratory mechanics; mechanical ventilation

In 1949, Buytendijk first showed that it was possible to use esophageal pressure as a surrogate for pleural pressure (1). In 1952, Dornhorst and Leathart showed that changes in pleural and esophageal pressures were similar and useful to understand respiratory mechanics (2). Soon thereafter, Cherniack and colleagues confirmed that changes in pleural pressure were similar to changes in esophageal pressure, although the absolute values of pressures in the pleural space were often more negative than in the esophagus (3). These

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findings indicated that measurements of esophageal pressure could provide an estimate of pleural pressure; such measurements have enhanced substantially our knowledge regarding the mechanical properties of the lungs, the chest wall, and the whole respiratory system. In addition, esophageal pressure measurements (and derived parameters such as work of breathing) have advanced our understanding of the pathophysiological mechanisms of acute respiratory failure and ventilator dependency. Surprisingly, however, these measurements have been used mostly in the field of research. Recent studies showing the usefulness of esophageal pressure measurements in ventilator management during acute lung injury, optimizing patient–ventilator interaction and ventilator weaning, have drawn the attention of clinicians and researchers to this "old" technique (4–7).

Despite data showing its usefulness in critically ill patients, esophageal pressure is still hardly used in the clinical arena. This is partially due to technical issues, such as the insertion and proper placement of an esophageal catheter, the feasibility of obtaining accurate measurements, and the interpretation of the measurements. For these reasons, a working group called PLUG (*Pleu*ral Pressure Working Group; *see* the online supplement) gathered together for a 1-day conference to summarize current knowledge on esophageal pressure measurements and to suggest ways in which these measurements could be used in critically ill patients. This review is focused on three main areas: (*1*) the physiological background of esophageal pressure measurement, (*2*) the clinical indications, and (*3*) the description of the technique.

Physiological Background

The Forces

Mechanical work is performed when a force moves its point of application through a distance. In pulmonary physiology, work is done when a pressure (expressed in cm H_2O) changes the volume (expressed in liters) of the system. The driving force for breathing is the intrathoracic pressure generated by the contraction of the respiratory muscles (active conditions), the ventilator substituting for respiratory muscles (passive conditions) or by both the ventilator and the respiratory muscles (assisted ventilation). The various trans-structural pressures involved in overcoming the loads imposed by the different respiratory structures (lungs, chest wall, and respiratory system) are listed in Table 1 and graphically shown in Figure 1.

During mechanical ventilation, the total pressure applied to the respiratory system (Ptotal) is the sum of the pressure provided by the ventilator (Paw) and the pressure generated by the patient's inspiratory muscles (Pmus):

$$\text{Ptotal} = \text{Paw} + \text{Pmus} \qquad (1)$$

The total pressure applied to the respiratory system must overcome the opposing forces produced by the elastic and resistive properties of the respiratory system. This relationship is described in the equation of motion:

$$\text{Ptotal} = \text{Paw} + \text{Pmus} = P_0 + \text{Ers}\cdot V + \text{Rrs}\cdot \dot{V} \qquad (2)$$

where P_0 is the value of Paw at the beginning of the breath (zero or a positive value of end-expiratory pressure), Ers is the respiratory system elastance, Rrs is the respiratory system resistance, V is the volume difference between the instantaneous volume and the relaxation volume of the respiratory system, and $\dot{V}$ is airflow. At the end of a controlled breath using constant flow insufflation, Equation 2 can be applied using delivered tidal volume for V and set inspiratory (peak) flow for $\dot{V}$. The values of Rrs and Ers are readily measured during passive mechanical ventilation using the end-inspiratory (and end-expiratory) occlusion technique (8).

Of note, the complete equation of motion also includes a third component describing pressure changes in phase with acceleration. This part can be reasonably neglected at conventional frequencies and gas densities, but becomes important under conditions of high-frequency ventilation. Last, in applying Equation 2, one must remember that the system is not linear, and at the extremes of lung volume, lung stresses may exceed those estimated from elastance.

Esophageal Pressure as a Surrogate of Pleural Pressure

In upright subjects, pleural pressure (Ppl) has been estimated by measuring esophageal pressure (Pes), using an esophageal balloon–catheter system. The respiratory changes in Pes are representative of changes in Ppl applied to the lung surface (9). The difference between Paw and Pes is a valid estimate of transpulmonary pressure (P_L) in the region surrounding the balloon catheter (9). Absolute values of Pes can be influenced by respiratory mechanics, lung volume, weight of the mediastinum, the abdomen, posture, reactivity of the esophageal smooth muscle wall, and mechanical properties of the balloon. Our knowledge about the impact of position, asymmetry of lung disease, lung and chest wall distortion (10), increased abdominal pressure, and large pleural effusion (11) on the observed Pes and its respiratory variation is limited. Some data suggest, however, that, even under these conditions, Pes remains an acceptable effective average Ppl (10).

As a consequence a debate exists about whether the absolute values of Pes can be interpreted as reliable absolute values of Ppl (12, 13). Data suggest that the use of absolute values of Pes is possible in the clinical setting (6, 14), but this approach needs further validation.

Pleural pressure varies within the pleural space because of both gravitational gradients and regional inhomogeneities. Furthermore, diseases that obstruct flow, increase the density of lung tissue, or stiffen the lungs could increase the interregional differences in Ppl. For the sake of simplicity, in this review we are assuming that Ppl is uniform throughout the pleural space. Pes is the most convenient way to measure Ppl.

Table 1: Trans-structural Pressures Related to Ventilation

Pressure difference across the respiratory system (Prs):

$$\text{Prs} = \text{Paw} - \text{Pbs}$$

Pressure difference across the lung (transpulmonary pressure, P_L):

$$P_L = \text{Paw} - \text{Ppl}$$

Pressure difference across the chest wall (Pcw):

$$\text{Pcw} = \text{Ppl} - \text{Pbs}$$

Alternatively:

$$\begin{aligned}\text{Prs} &= P_L + \text{Pcw}\\ &= \text{Paw} - \text{Ppl} + \text{Ppl} - \text{Pbs}\\ &= \text{Paw} - \text{Pbs}\end{aligned}$$

Definition of abbreviations: Paw = airway pressure, measured by the ventilator at the proximal end of the airways; Pbs = body surface pressure; Ppl = pleural pressure.

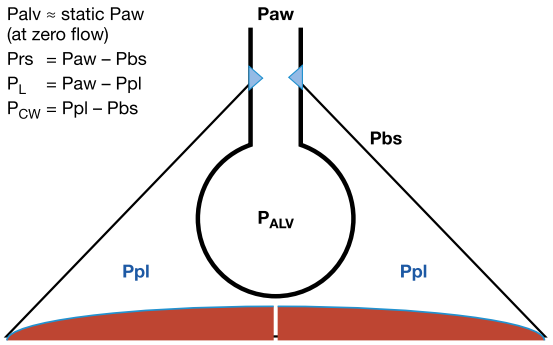

Figure 1. Schematic representation of the relevant pressures for the respiratory system. Pbs= pressure at body surface; Pcw = pressure difference across the chest wall; P_L = transpulmonary pressure; Prs = pressure difference across the respiratory system.

Passive Inflation of the Thorax

Under passive conditions, the pressure applied to move gas into the lung is delivered by the ventilator and is equal to Paw. Because Pmus is zero, the equation of motion can be rewritten as follows:

$$\text{Paw} = P_0 + (\text{Ers}\cdot\text{V}) + \left(\text{Rrs}\cdot\dot{\text{V}}\right) \quad (3)$$

As Ers is the sum of Ecw and E_L:

$$\text{Paw} = P_0 + (\text{Ecw}\cdot\text{V}) + (E_L\cdot\text{V}) + \left(\text{Rrs}\cdot\dot{\text{V}}\right) \quad (4)$$

Paw, V, and $\dot{\text{V}}$ are continuously measured by the ventilator. Under conditions of no flow, such as during end-inspiratory or end-expiratory occlusion maneuvers, the resistive pressure component ($\text{Rrs}\cdot\dot{\text{V}}$) of Equations 3 and 4 vanishes and the unknown variables of Equations 3 and 4 are Ecw and E_L (Pcw and P_L change per unit of volume). The measurement of Pes is the only way to distinguish what fraction of Paw is applied to overcome lung and chest wall elastance. It should be clarified that P_L incorporates the pressure difference across the airways and the alveoli. The difference between alveolar pressure and pleural pressure is the transalveolar pressure. In the absence of flow (e.g., during an end-inspiratory occlusion maneuver to obtain the plateau pressure or an end-expiratory occlusion to measure total and auto- or intrinsic positive end-expiratory pressure [15]), and provided that there is no significant airway closure, the Paw measured by the ventilator is equal to the pressure inside the alveoli.

Active Inflation of the Thorax

We refer to "active" conditions when the respiratory muscles are working, irrespective of the work done by the ventilator. In patients with spontaneous breathing efforts, Pmus becomes a significant component of the equation of motion (Equation 2).

In this condition, the Paw displayed by the ventilator poorly reflects the total distending pressures of the lungs, and the measurement of pleural pressure or Pes is needed for an accurate P_L estimation. One may consider that the pressure applied to distend the lungs is the sum of a visible component (displayed ventilator pressure, i.e., airway pressure) and an invisible component (Pes). Figure 2 illustrates the possible differences between volume control and pressure control regarding the effects of spontaneous breathing on P_L.

In the presence of spontaneous breathing efforts while receiving mechanical ventilation, direct measurement of the level of effort may help the clinician to better adjust the ventilator settings and/or the sedation level. Respiratory muscle effort can be assessed by calculating work of breathing (WOB) and the pressure–time product (PTP) of the esophageal pressure (PTPes), reflecting the effort done by all of the respiratory muscles, or the pressure–time product of the transdiaphragmatic pressure (PTPdi), reflecting mostly the effort done by the diaphragm. Transdiaphragmatic pressure (Pdi) is calculated as the difference between the gastric pressure and Pes.

Measuring WOB or PTP is a useful approach to estimate the energy dissipated or consumed by the respiratory muscles (16). Work is expressed as force × displacement. In physiology, the work performed during each respiratory cycle (from the beginning of inspiratory flow, t_0, to the end of inspiration, T_i, is expressed as the area enclosed in a pressure (P)–volume (V) diagram:

$$\text{WOB} = \int_{t_0}^{T_i} \text{PV}\, dt$$

In a spontaneously breathing patient, work measurement requires an estimate of Ppl, and Pes provides an accurate estimate. Pes can be viewed as the static recoil pressure of the relaxed chest wall (Pcw,rel) minus the inspiratory pressure developed by the inspiratory muscles in expanding the chest wall (Pmus). As lung volume increases, Pcw,rel and the respiratory muscles generate a negative pressure relative to this value. Pmus can be expressed as

$$\text{Pmus} = \text{Pcw,rel} - \text{Pes} \quad (5)$$

The work performed by respiratory muscles (Wmus) equals the integral of the product of Pmus and the change in volume:

$$\text{Wmus} = \int \text{Pmus}\cdot d\text{V} \quad (6)$$

By combining Equations 5 and 6, the following is obtained:

$$\text{Wmus} = \int (\text{Pcw,rel} - \text{Pes})\cdot d\text{V} \quad (7)$$

The dynamic relation between Pmus and lung volume during breathing can be expressed graphically using the Campbell diagram (17).

Respiratory muscle activity can also be quantified using PTPes. Like WOB, it is based on the estimation of Pmus but it refers to the integral of pressure over time and not over volume. PTPes is therefore the product of the pressure developed by the respiratory muscles multiplied by the time of muscle contraction, expressed in units of cm H_2O × second. It can be used whether or not volume is generated. When volume is generated, WOB and PTPes are usually tightly correlated.

The WOB per breathing cycle is normally expressed in joules. Work per minute is calculated by multiplying the WOB per cycle by the corresponding respiratory frequency. Work per liter is calculated by dividing work per minute by minute ventilation. One joule is the work needed to move 1 L of air across a 10–cm H_2O pressure difference (i.e., the surface enclosed in a rectangle with a base of 10 cm H_2O and a height of 1 L).

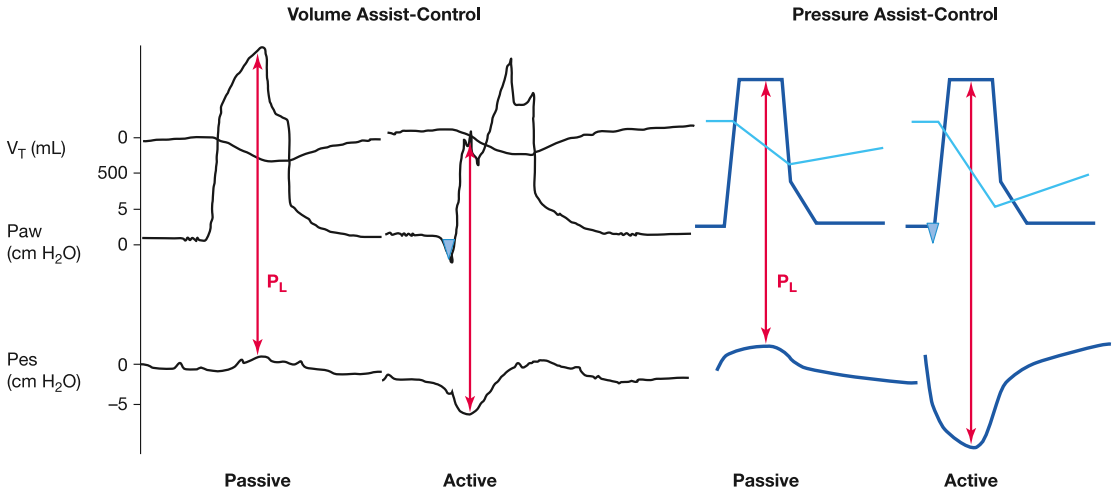

Figure 2. Comparison of volume-assist control and pressure-assist control ventilation with recordings of tidal volume (V_T) and airway and esophageal pressure (Paw and Pes, respectively) waveforms. The *red arrows* illustrate the difference between airway and esophageal pressure, that is, transpulmonary pressure or P_L. P_L increases with the patient's effort only during pressure control.

Excellent correlations between WOB and oxygen consumed by, or blood flow to, the respiratory muscles have been shown under experimental and clinical conditions (18–20). Measurements of WOB, however, can sometimes underestimate oxygen consumption by the respiratory muscles. In particular, measurement of mechanical work is totally insensitive to energy expenditure during isometric contraction (21). In addition, mechanical work does not account well for the duration of muscular contraction. PTPes potentially circumvents these problems. It has been shown that PTPdi, under specific experimental conditions, is more closely related to respiratory muscle oxygen consumption than WOB (22).

Few studies have been conducted in healthy subjects to determine the normal range of WOB and muscular effort. During spontaneous breathing, WOB ranged from 2.4 to 7.5 J · minute^{-1} and from 0.20 to 0.9 J · L^{-1} (23–25). Normal values of PTPes range from 50 to 150 cm H_2O · second · minute^{-1} (average, 86 ± 21 cm H_2O · s · min^{-1}) (25). The respiratory work performed by patients receiving partial ventilator assistance can become considerably higher than normal. For example, when patients receive an intermittent mandatory ventilation rate of 10 breaths/minute or pressure support of 7 cm H_2O, common settings in clinical practice, inspiratory PTPes can exceed 200 cm H_2O · second · minute^{-1}, which was double the value recorded in healthy subjects (26).

In the clinical setting, measurement of inspiratory effort may be monitored as the simple changes of Pes during inspiration, that is, not taking into account the static recoil pressure of the relaxed chest wall. It is much less precise than measurements of Pmus or Pdi but it may be used as a bedside monitoring tool, as done in some sleep studies or during a weaning trial (5, 27).

Clinical Use of Esophageal Pressure: Passive Conditions

Interpretation of Pressures Displayed by the Ventilator

In sedated and paralyzed subjects, positive pressure ventilation is titrated on the basis of Paw, with the expectation that it closely approximates P_L. In patients with normal Ecw, Paw is a reasonable surrogate for P_L. When Ecw is high, however, Paw may be significantly higher than P_L. Indeed, a portion of Paw is dissipated in distending the chest wall. As the chest wall becomes stiffer, the proportion of Paw that distends the lung (P_L) decreases progressively. Ecw can be elevated in patients with acute respiratory failure for various reasons (28). Increases in Ecw and/or in Ppl can occur as a result of intraabdominal hypertension, pleural effusion, massive ascites, thoracic trauma, and edema of the intrathoracic and intraabdominal tissues as a result of fluid resuscitation (29–32). In pigs, Mutoh and colleagues have shown that intravascular volume infusion produces abdominal distension, lung volume restriction, and stiffening of the chest wall, which, in turn, resulted in increases in pleural pressure, Ecw, and E_L (33). In a swine model of acute respiratory distress syndrome (ARDS) caused by oleic acid infusion, Quintel and colleagues showed that increasing abdominal pressure by insufflation of air into the peritoneal cavity increased Pes, decreased lung volume, and markedly increased edema of intrathoracic tissues (34). These studies suggest that similar mechanisms (intravascular volume infusion, insufflation of air into the peritoneal cavity, tissue edema, etc.) may lead to increased Ecw and increased Ppl in patients, especially in the context of ARDS. Moreover, several investigators have reported the influence of increased Ecw on the pressure–volume curve of the respiratory system both in terms of elastance value and of shape of the curve (30, 35, 36).

Because Ecw may vary greatly among individuals, adjusting the ventilator settings only on the basis of Paw may not be a satisfactory strategy when ventilating subjects with ARDS. In fact, a positive pressure breath may injure the lung if it results in end-inspiratory alveolar hyperinflation and/or cyclical alveolar opening and collapse (37). Provided P_L is the real "lung-distending" pressure, that is, the main force that promotes alveolar recruitment and lung inflation, a lung-protective ventilator strategy should take this concept (P_L) into account. Esophageal pressure measurement makes this possible in clinical practice. Figure 3 illustrates three

different clinical situations with different contributions of the chest wall.

Esophageal Pressure to Guide Therapy in ARDS

The usefulness of Pes in guiding therapy in ARDS has been shown in the Esophageal Pressure–Directed Ventilation (EPVent) study (6). Because of reduced chest wall compliance, edema, or abdominal distension, Pes is often elevated in patients with ARDS, and the calculated P_L can be negative at end expiration. This may indicate closed airways, or flooded or atelectatic lung. Positive end-expiratory pressure (PEEP) could thus be increased until P_L becomes positive at end expiration to keep airways open (with the caveat that positive values do not ensure open alveoli in the zones distal to the sampling catheter). In their single-center, randomized controlled trial, the EPVent investigators compared mechanical ventilation guided by Pes measurements (experimental arm) with ventilation based on the protocol of the U.S. National Health Institutes–sponsored ARDSNetwork (control arm) (38). Patients in the control arm were treated with tidal volume set at 6 ml/kg of predicted body weight and PEEP based on the patient's partial pressure of arterial oxygen (Pa_{O_2}) and inspired fraction of oxygen ($F_{I_{O_2}}$). In the experimental arm, PEEP levels were set to achieve a P_L between 0 and 10 cm H_2O at end expiration, according to a sliding scale based on the $Pa_{O_2}/F_{I_{O_2}}$ ratio. They also limited tidal volume to keep P_L at less than 25 cm H_2O at end inspiration. At 72 hours, PEEP was on average 18 $\pm$ 5 cm H_2O in the experimental arm and 12 $\pm$ 5 cm H_2O in the control arm. The study was terminated early, after enrolling 61 patients, for an overwhelming effect of the Pes strategy on blood oxygenation. At 72 hours, the $Pa_{O_2}/F_{I_{O_2}}$ ratio was 280 $\pm$ 126 mm Hg in the Pes arm and 191 $\pm$ 71 in the control arm ($P = 0.001$). Respiratory system compliance was also significantly improved in the Pes group ($P = 0.005$), probably as a consequence of improved recruitment. Although this trial showed a trend toward reduced 28-day mortality (17 vs. 35%; $P = 0.055$), it was not sufficiently powered to show significant change in any outcome variable such as ventilator-free days, length of stay, duration of ventilation, or long-term clinical status. Nevertheless, this research may be considered proof of

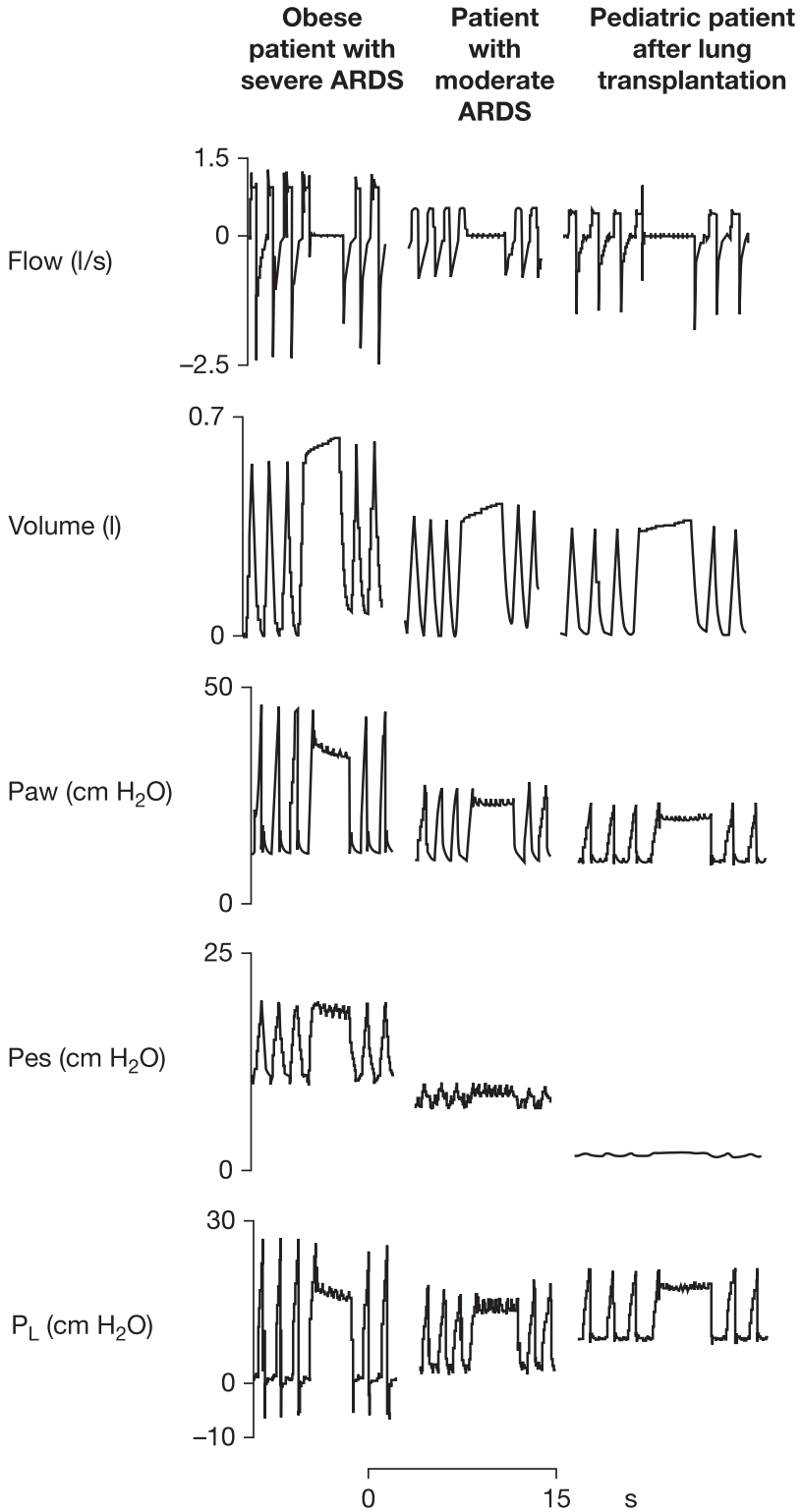

Figure 3. Three different clinical situations with different contributions of the chest wall to the pressure generated by the ventilator (Paw) during passive inflation. Despite different levels of Paw, the end-inspiratory P_L is almost similar in the three patients. From *top* to *bottom*: tracings of flow, volume, and esophageal, airway, and transpulmonary pressure. ARDS = acute respiratory distress syndrome; Paw = airway pressure; Pes = esophageal pressure; P_L = transpulmonary pressure.

concept for the usefulness of Pes measurements in ARDS.

Other investigators have used an elastance-derived method to estimate Ppl, which neglects the absolute values and relies on the tidal Pes swings (ΔPes) to calculate Ecw, that is, Ecw = ΔPcw/V_T (tidal volume) (39). This method takes into account the lung-distending pressure applied by positive pressure inflation during mechanical ventilation. Because any positive pressure applied at the airway opening acts on two elastic structures connected in series (the lung and the chest wall), Paw is distributed between chest wall and lung elastance. The ratio of lung to respiratory system elastance can be used to better interpret the effect of Paw. Accordingly,

$$P_L = Paw \cdot (E_L/Ers)$$

in which $E_L = \Delta P_L/V_T$ and Ers = ΔPaw/V_T under static conditions (zero flow) between the beginning and the end of a breathing cycle.

The latter method for partitioning lung and chest wall elastance has been used to guide a transpulmonary "open lung" approach in a cohort of patients with severe ARDS related to influenza A-H1N1 (4). This assessment helped clinicians to decide, in severely hypoxemic patients requiring high Paw pressures, whether it was appropriate to further increase pressures on the ventilator or whether an extracorporeal oxygenation technique was preferable.

Although further studies are needed to test alternative methods of calculating P_L, the results from such studies support the use of Pes measurement in sedated and paralyzed subjects in titrating ventilator settings in ARDS.

The Esophageal Catheter in the Operating Room

Data suggest that the ventilatory settings during surgical procedures can have important clinical consequences on postoperative complications (40, 41). General anesthesia or selected surgical procedures such as peritoneal insufflation of gas or positioning can affect the mechanics of the chest wall (42). Obese patients or patients with increased abdominal pressure, scoliosis, spondylitis, fibrothorax, or pleural effusion also have altered chest wall mechanics (43). In all of these circumstances, monitoring of Paw during or after surgery may not be representative of the distending pressure applied on lung tissue (i.e., the stress) and the resulting deformation (i.e., the strain). Although not proven, monitoring of Pes could be helpful to better customize ventilator settings in all these circumstances.

Understanding the Filling Pressures of the Heart

Because the heart is in the chest, the correct interpretation of intracardiac pressures as filling pressures for the ventricles needs to refer the values of absolute intravascular pressures to the changes in extracardiac pressure or pericardial pressure. This is particularly relevant during changes in lung volume under positive airway pressure. Mean Pes is the more convenient technique to estimate extramural pressure and therefore the transmural filling pressures, that is, the intravascular minus the surrounding extravascular pressure (44, 45). A correct interpretation of the cardiac function curve, also known as the Frank–Starling relation, must take into account the transmural filling pressure, not the intravascular pressure (46). Consequently, for similar intravascular pressures, the transmural filling pressures are usually lower when patients are ventilated with positive pressure ventilation as compared with unassisted spontaneous breathing.

Clinical Use of Esophageal Pressure: Assisted, or Patient-triggered, Mechanical Ventilation

General Issues with Assisted, or Patient-triggered, Ventilation

During spontaneous breathing Pes can be used to assess respiratory muscle effort and WOB generated by the patient. We now summarize some of the clinical scenarios in which this measure may be useful.

There is a complex interplay between the assistance delivered by the ventilator and the motor activity of the respiratory system. For monitoring patient–ventilator interactions, clinicians rely mostly on pulse oximetry, arterial blood gas values, and Paw–flow waveforms that are available on most ventilators. Several clinical research studies have demonstrated how difficult it is to determine the amount of effort in standard ventilatory modes (18, 47–50) and the presence of asynchrony (26, 51, 52). Relying on measurements of Paw and flow may mask profound asynchrony between the patient and the ventilator (52–54).

Although unloading respiratory muscle activity and avoiding excessive respiratory muscle work constitute a major objective of mechanical ventilation, this has surprisingly not been monitored until recently (55). Monitoring Pes activity offers the potential to monitor patient–ventilator interactions.

Monitoring of Respiratory Muscle Activity and Synchrony during Assisted Ventilation

- When the ventilator does not detect any "patient triggering" and the patient is highly sedated, the presence of respiratory muscle contractions triggered by the ventilator has been described in critically ill patients (56). This phenomenon, known as respiratory entrainment (57), was called *reverse triggering* because the insufflation triggers the respiratory muscle contraction (56). These efforts become evident if respiratory muscle activity is monitored through the measurement of Pes (*see* Figure 4). This may have important clinical consequences such as double inspiration, tidal volume increase, or erroneous plateau pressure measurements.
- Pressure-preset or pressure-targeted ventilation modes work with the ability to synchronize pressure delivery with patient inspiratory efforts. When lung-protective ventilation is desirable, clinicians should be aware that inspiratory synchronization may amplify patient effort. Such a synchronization may be potentially harmful by increasing P_L and V_T values (58). When lung protection is considered a priority but a certain degree of spontaneous breathing activity is maintained, monitoring of Pes may be the best way to ensure proper delivery of inspiratory assistance.
- During assisted ventilation, the combination of slightly excessive pressures and volumes to assist the patient, as well as excessive ventilator inspiratory time relative to a patient's neural inspiratory time and to some degree of airway obstruction, may lead to the occurrence of ineffective or missed efforts (26, 51, 52, 59). During the presence of these wasted efforts, the real respiratory rate of the patient can be

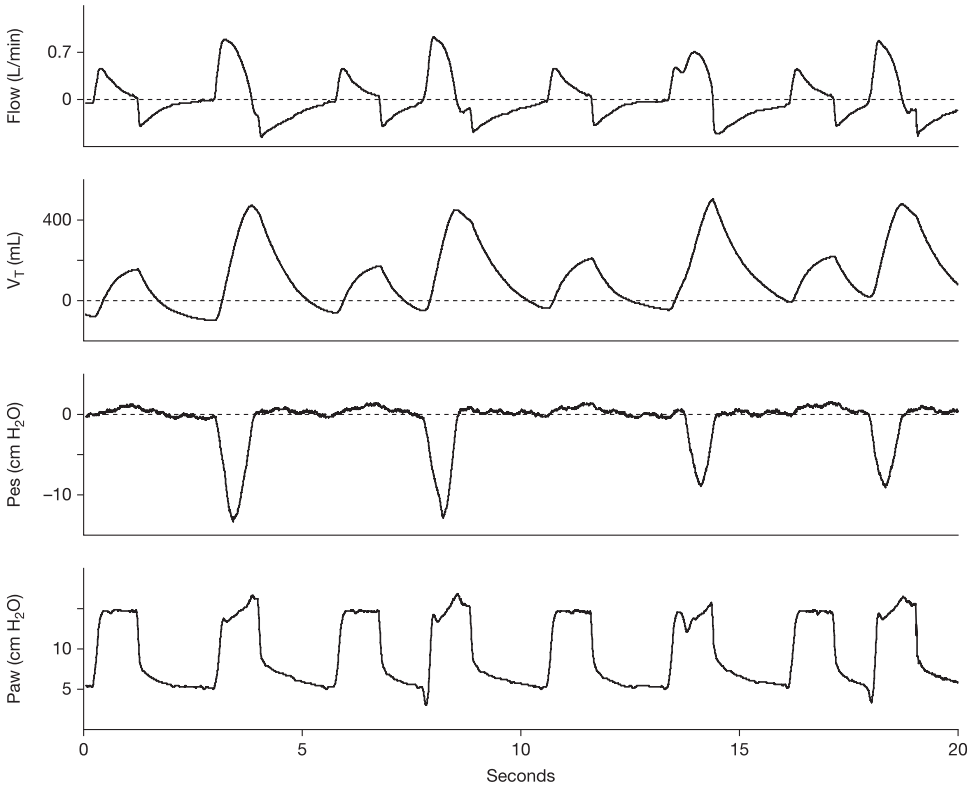

Figure 4. Effects of intermittent spontaneous breathing efforts indicated by negative esophageal pressure swings during a bilevel mode of ventilation. The airway pressure tracing alone does not allow one to understand what the patient is doing. From *top* to *bottom*: tracings of flow, volume, esophageal pressure, and airway pressure. Paw = airway pressure; Pes = esophageal pressure; V_T = tidal volume.

twice the rate displayed on the ventilator (7, 60). Monitoring Pes or the electrical activity of the diaphragm is helpful in recognizing and treating the cause of ineffective efforts (7). Because this asynchrony is associated with prolonged duration of mechanical ventilation, this may potentially impact the duration of mechanical ventilation. In injured lungs, relatively strong negative Ppl generated by diaphragm contraction may have regional effects in dependent regions that are not uniformly transmitted, causing pendelluft (61). In such cases, the risks associated with large P_L swings may even be underestimated by Pes.

- Short cycles result from a shorter mechanical inspiratory time than the patient's neural inspiratory time (52, 62). The combination of high respiratory drive, high flow rate, and low tidal volumes makes this problem frequent. A real-time online monitoring of respiratory muscle activity, such as Pes or diaphragmatic electromyographic activity, is important to detect the degree of synchronization between the patient's inspiratory efforts and the insufflation time of the ventilator.

Measurement of Auto- or Intrinsic PEEP

For lung volume to increase in a patient with intrinsic PEEP (PEEPi), the inspiratory muscles must contract and generate an amount of pressure equal to the dynamic component of total PEEP, also referred to as PEEPi, before any volume is displaced. The most accurate method to quantify PEEPi is to measure the drop in esophageal pressure at end expiration at the point of the contraction of the inspiratory muscles until inspiratory flow starts (63). Although expiration normally occurs passively, the coexistence of PEEPi and active expiration is common, especially in patients with chronic obstructive pulmonary disease (64). Positive expiratory swings in gastric pressure are observed during active expiration as a consequence of abdominal muscle recruitment. In this scenario, when the patient starts contracting the inspiratory muscles, the expiratory muscles also start to relax. The drop in esophageal pressure used to estimate PEEPi is therefore due to the relaxation of the expiratory muscles. To avoid overestimating the value of PEEPi, the abdominal pressure swing resulting from the active expiration should be subtracted from the initial drop in esophageal pressure as first proposed by Lessard and colleagues (64).

Weaning from Mechanical Ventilation

Measurement of WOB can be a useful monitoring tool during a weaning trial (65). Research into weaning pathophysiology has revealed that respiratory effort changes progressively as patients fail a weaning trial (66–69). Over the course of a spontaneous breathing trial, PTPes remained unchanged in weaning success patients (66). In contrast, weaning failure patients developed marked and progressive increase in PTPes as a result of an increase in the mechanical load on the respiratory muscles. By the end of the trial, the weaning failure patients increased their PTPes to more than four times the normal value (66). Over the course of a failed weaning trial, swings in

Pes showed larger changes than did the rapid shallow breathing index (66); accordingly, Pes measurements may provide a simple method for monitoring changes in patient effort. Jubran and colleagues (5) showed that looking at trends in Pes (the Pes trend index) over a weaning trial might be more helpful than spot measurements in weaning prediction. If confirmed, measurement of the Pes trend index could provide a useful clinical tool for patient assessment during weaning. In addition, increases in Pes swings during the trial could alert a physician to search for possible causes and to institute therapy, such as bronchodilators, inotropes, vasodilators, or diuretics.

In addition to its monitoring role, measuring Pes during spontaneous breathing helps in our understanding of the hemodynamic changes that occur during difficult weaning (67, 70). Specifically, the large negative swings in Pes that occur during difficult weaning account for the increases in venous return into the pulmonary circulation and in left ventricular afterload caused by the increased transmural intrathoracic pressures (71).

Technique

The Balloon Catheter

Pes can be measured using catheters with air-filled or liquid-filled balloons (mainly in neonates) (2), or with small transducers placed in the esophagus (72). The most common technique is to use a catheter with a thin-walled latex balloon sealed at its distal port and filled with air (3). The Pes signal is transmitted through the catheter and is measured at its proximal end by a pressure transducer.

Each type of esophageal balloon (depending on its diameter and length) requires the injection of a specific amount of air (ranging from 0.5 to 4 ml) to measure Pes correctly (73). The accuracy of Pes monitoring with an esophageal balloon depends on the volume injected (74, 75). For the same amount of air inside the balloon, the measured Pes is significantly higher with balloons of narrower diameter and shorter length than with larger and longer balloons (74, 75). A longer balloon is preferable because it can record pressure from a larger area of the esophageal wall, thus better reflecting Ppl along its length (74, 76). To optimize signal transmission to pressure transducers, the balloon should have high compliance. Balloons that are commonly used are 5 to 10 cm long, 0.01 to 0.18 mm thick, and 3.2 to 4.8 cm in diameter (74, 77). It has been shown that the presence of the nasogastric tube does not invalidate the accuracy of Pes measurements provided that the catheter is correctly positioned (78). Naso- or orogastric tubes

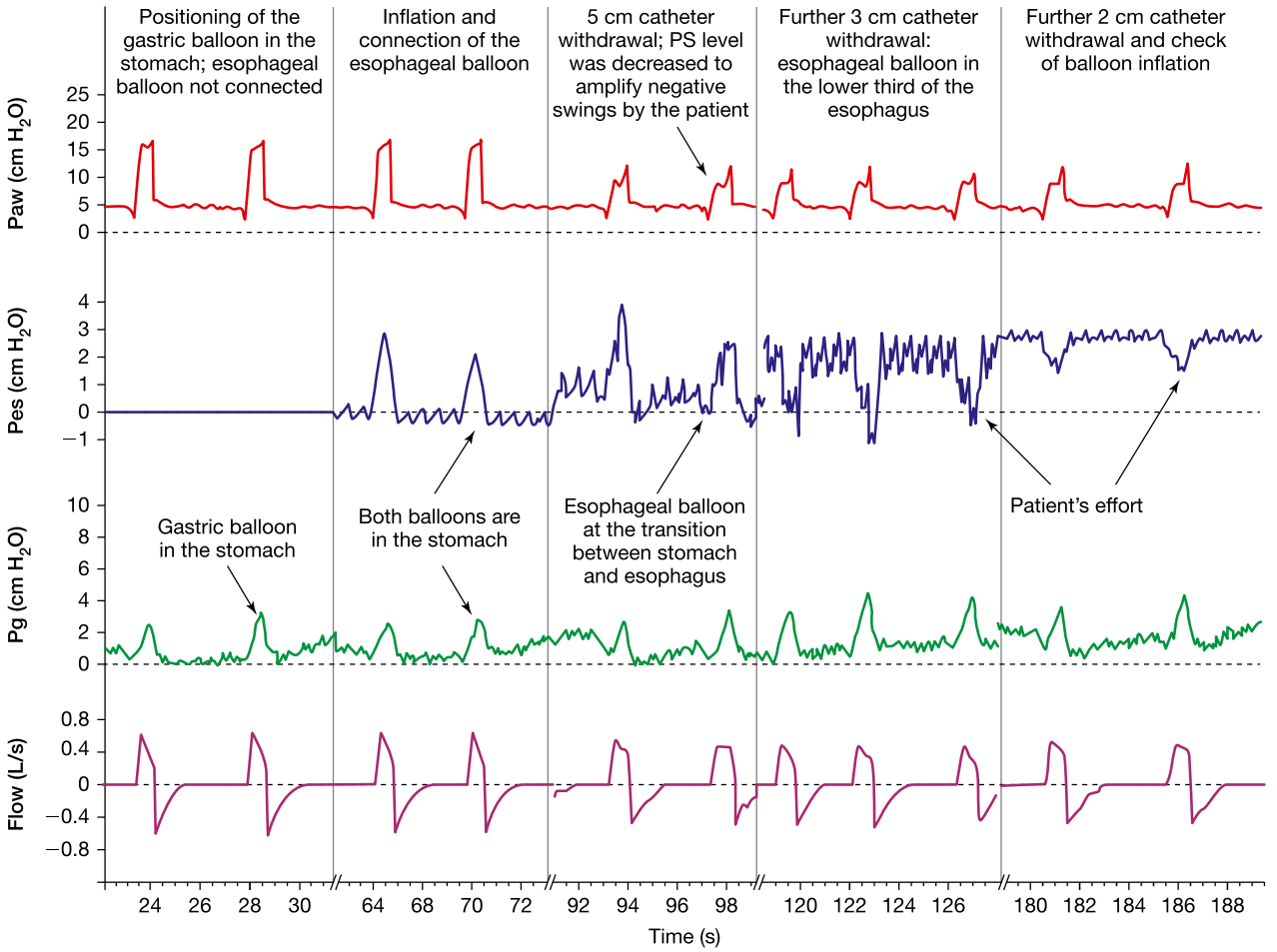

Figure 5. Pressure waveforms during insertion of an esophageal catheter. Paw = airway pressure; Pes = esophageal pressure; Pg = gastric pressure; PS = pressure support.

equipped with an esophageal balloon are now available (79): these devices are recommended if measurements of Pes are required for a long period. These tubes can also be equipped with two balloons for measuring esophageal and gastric pressures.

The Procedure for Catheter Placement

After placing the patient in a semirecumbent position and anesthetizing the nose and oropharynx, the catheter is inserted through the nostril. The empty balloon catheter is advanced into the stomach, at which time the balloon is inflated, usually with 0.5 ml of air (this volume can, however, vary with the characteristics of the system [80, 81]). The distal part of the catheter is connected to a pressure transducer, which, in turn, can be connected to a dedicated acquisition system, a patient-monitoring system or an auxiliary pressure port of the ventilator. The presence of a positive pressure deflection during a spontaneous inspiration generally indicates that the balloon is in the stomach, provided that there is no diaphragmatic paralysis. Subsequently the catheter is slowly withdrawn until a negative pressure deflection replaces the positive deflection, indicating that the balloon is in the lower third of esophagus (82, 83) (Figure 5). The dynamic occlusion test is then performed (*see below*) (77). Reassessment of the correct volume of air in the balloon and the control of its proper positioning are particularly important to ensure reliable measurements of Pes over a prolonged period of time.

Validation of Esophageal Pressure Measurement: The Dynamic Occlusion Test

In a spontaneously breathing patient, the classic method to validate the Pes measurement is the dynamic occlusion test. It consists of measuring the ratio of change in esophageal pressure to the change in airway opening pressure (ΔPes/ΔPaw ratio) during three to five spontaneous respiratory efforts against a closed airway. A ΔPes/ΔPaw ratio close to unity indicates that the balloon provides a valid measure of Ppl changes (77) (Figure 6). This test does not require patient cooperation. The occlusion test has been validated in normal adults and pediatric patients; it has also been applied in paralyzed subjects (84–87). In sedated and paralyzed patients, the occlusion test is performed by applying manual compression on the chest during airway occlusion (84–86) (Figure 6).

Factors influencing the ΔPes/ΔPaw ratio during the occlusion test include the position of the balloon, the amount of air injected into the balloon, the patient's position, and lung volume. These factors should be checked periodically to ensure the best concordance between swings in Pes and in Paw during the occlusion test. The acceptable range of ΔPes/ΔPaw ratio during the occlusion test is 10–20% (i.e., from 0.8 to 1.2) (85, 86, 88). Cardiac contractions can distort the Pes signal. Patient position, balloon position, and lung volume may influence the amplitude of Pes changes due to the cardiac artifact (89). Esophageal contraction due to peristalsis is sometimes present and is easily detected (as a large increase in pressure that bears no relationship with respiratory cycles): in this case, Pes measurement should be interrupted until Pes returns to its baseline value.

Conclusions

With rapid advances in technology, monitoring of Pes can be safely, satisfactorily, and easily performed at the bedside in the intensive care unit. Despite voluminous data showing the usefulness of Pes measurements in critically ill patients, the introduction of Pes measurements in the intensive care unit has been disappointingly slow.

Pes measurements allow the partitioning of respiratory system mechanics into pulmonary and chest wall

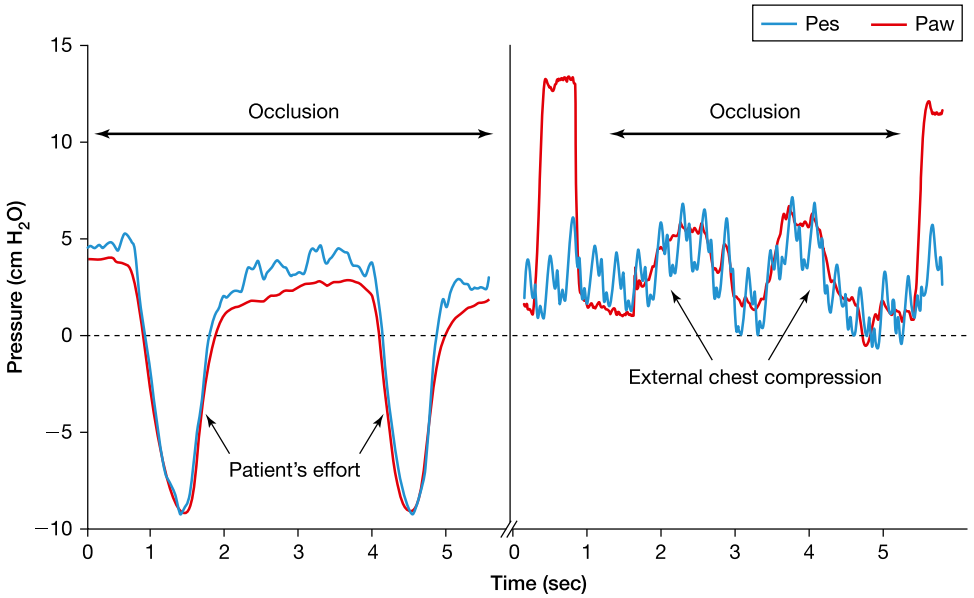

Figure 6. Occlusion test in a spontaneously breathing patient (*left*) and in a paralyzed patient (*right*). In the former case, the airway has been occluded during patient effort; in the latter case, the airway has been occluded while applying an external chest compression. Paw axis has been shifted to achieve overlap of the two signals. Paw = airway pressure; Pes = esophageal pressure.

components. As such, Pes measurements have enhanced our understanding of the pathophysiology of acute lung injury, patient–ventilator interaction, and weaning failure. By providing a practical means of quantifying respiratory effort, Pes measurements may make it feasible to individualize the level of muscle unloading during mechanical ventilation and may provide a useful clinical tool for assessing patients during a weaning trial. The use of Pes measurements in PEEP titration may help improve oxygenation and compliance in patients with ARDS.

Improved outcome has been demonstrated when physiological principles (low tidal ventilation [38], high PEEP [90], prone position [91], or neuromuscular blocking agents [92]) are applied in ventilator management of patients with ARDS. The time is now right to take advantage of the body of knowledge obtained with Pes and apply it to improve the management of critically ill and ventilator-dependent patients. ■

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