Esophageal pressures in acute lung injury: do they represent artifact or useful information about transpulmonary pressure, chest wall mechanics, and lung stress?

Stephen H. Loring,1,5 Carl R. O'Donnell,2,5 Negin Behazin,1,5 Atul Malhotra,3,5 Todd Sarge,1,5 Ray Ritz,1 Victor Novack,4 and Daniel Talmor1,5

1Department of Anesthesia, Critical Care, and Pain Medicine and 2Division of Pulmonary, Critical Care, and Sleep Medicine, Beth Israel Deaconess Medical Center, 3Divisions of Pulmonary and Critical Care and Sleep Medicine, Brigham and Women’s Hospital, 4Harvard Clinical Research Institute, and 5Harvard Medical School, Boston, Massachusetts

Submitted 29 July 2009; accepted in final form 14 December 2009

Loring SH, O’Donnell CR, Behazin N, Malhotra A, Sarge T, Ritz R, Novack V, Talmor D. Esophageal pressures in acute lung injury: do they represent artifact or useful information about transpulmonary pressure, chest wall mechanics, and lung stress? J Appl Physiol 108: 515–522, 2010. First published December 17, 2009; doi:10.1152/japplphysiol.00835.2009.—Acute lung injury can be a significant determinant of lung health in this population. PEES and end-expiratory transpulmonary pressure are important determinants of lung health in this population. Pes has been used for decades to estimate an effective pleural pressure (Ppl) between the lung and chest wall in healthy subjects and patients who are upright (10, 20, 40, 43). Because pleural pressure varies from place to place because of the gravitational gradient and other factors (27), there is no single value of pleural pressure. However, there is always an “effective” value of pleural pressure that, if it were applied to the whole pleural surface, would result in the observed lung volume and flow. To distinguish local and effective pressures, in this report, Ppl will denote the theoretical, unmeasured, effective pleural pressure that probably approximates the local pleural pressure at midlung height in the supine posture. By extension, we define an effective transpulmonary pressure (Pt = airway pressure – Ppl) as a theoretical pressure difference between the airway opening and the pleural space (34). Pt is to be distinguished from the corresponding estimated transpulmonary pressure, usually measured with an esophageal balloon (Pt,es = airway pressure – Pes).

Despite its longstanding use in upright patients and healthy subjects, there is widespread skepticism that Pes measurements reflect Ppl in patients who are supine, especially those with critical illness (12, 21). In particular, Pes values measured in supine critically ill patients are often much greater than what many assume to be likely pleural pressures. In this report, we argue, to the contrary, that Pes can be used to estimate credible values of Ppl. To be sure, there are differences between Pes and the effective Ppl in the supine position caused by the weight of mediastinal contents and other factors. The possibility remains, however, that the inaccuracies in estimating Ppl are minor...
compared with the differences in Pes among patients. Imperfect measurements can still be meaningful and useful, as was demonstrated in our recent clinical study (45).

To explore the potential utility of Pes measurements in critical illness, we describe measurements in patients with ALI/ARDS and use Pes measurements to infer the pressures acting on the lung and chest wall. Our aim is to determine whether the values of Pes measured in our patients are consistent with expectations based on fundamental principles of lung and chest wall mechanics. We postulate that Pes is an indicator, albeit imperfect, of an effective Ppl in critically ill semirecumbent patients and discuss the implications of these measurements for management of mechanical ventilation in patients with ALI/ARDS.

**Glossary**

- **VT** Tidal volume
- **PEEP** Positive end-expiratory (airway) pressure
- **PEEP** Positive end-expiratory occlusion
- **Pplat** Plateau (airway) pressure during end-inspiratory occlusion
- **Ppl** True pleural pressure at midlung height
- **PL** True transpulmonary pressure at midlung height (using Ppl)
- **PesL** Esophageal pressure
- **PesEEO** Ps measured during end-expiratory occlusion
- **PesEEO** Ps measured during end-expiratory occlusion (plateau)
- **Pga** Gastric pressure
- **Pblad** Bladder pressure
- **EL** Lung elastance
- **Ecw** Chest wall elastance

**METHODS**

This was a parallel physiological study of 48 patients enrolled in the EPVent Trial (45) at Beth Israel Deaconess Medical Center. In 51 of the 62 patients, initial measurements were made simultaneously with two recording systems, one for making clinical recordings used in the clinical trial and the other for making recordings used for subsequent analysis. Eleven patients in the clinical trial were not studied with the physiological system because of scheduling problems. Here we report an analysis of all 48 physiological records in which technically adequate pressure, volume, and flow measurements were recorded during baseline (pretrial intervention) ventilation. (Three of the physiological recordings were not analyzed: 2 lacked data recorded during end-expiratory occlusion, and 1 lacked data recorded before trial intervention.) The study was approved by the Institutional Review Board of Beth Israel Deaconess Medical Center, and prior informed written consent was obtained from the patients or their healthcare proxy.

**Physiological Measurements**

Airflow was measured with a pneumotachograph (Fleisch no. 1, available from PhippsBird.com) and integrated to obtain tidal volume (VT). Airway pressure was measured at the endotracheal tube. Gastric and esophageal pressures (Pga and Pes) were measured with an esophageal balloon-catheter (Ackrad Laboratories, available from CooperSurgical.com). The balloon (9.5 cm long, 2 cm perimeter) was filled with 0.5–1.0 ml of air. Frequency response of the system was adequate (without significant delays) up to 15 Hz. Pressure, volume, and flow measurements were displayed and recorded using a custom-written program and analyzed with Windaq software (Dataq.com).

**Protocol**

Patients were studied in the supine position, with the head of the bed elevated 30° (to prevent ventilator-associated pneumonia), on controlled mechanical ventilation with preintervention ventilator settings. They were sufficiently sedated to permit measurements of passive elastic recoil pressures of the respiratory system during mechanical ventilation. Bladder pressure (Pblad) was measured in 36 subjects via urinary catheter using standard techniques, with 50 ml of saline in the bladder and with the transducer referenced to the level of the pubic symphysis (32). In 35 subjects in whom it was possible, the esophageal balloon-catheter was first passed through the lower esophageal sphincter into the stomach for measurement of Pga at end expiration during mechanical ventilation. In all subjects, the balloon’s tip was repositioned to 40 cm from the incisors for recording Pes using techniques validated previously (46). Balloon position in the lower esophagus, which could not be confirmed by the occlusion technique in patients who were not making respiratory efforts, was confirmed by the presence of cardiac pulsation in the pressure trace, by appropriate pressure deflections during mechanical ventilation and a gentle push on the abdomen, and, in one case, by chest X-ray. In subjects in whom the pressure was initially recorded in the stomach, a change in pressure and respiratory and cardiac waveforms during withdrawal confirmed movement of the balloon into the esophagus. Airway pressure, Pes, and PLL were measured during an end-inspiratory occlusion (EIO) to obtain Pplat, PesEEO, and PLL, respectively. The corresponding pressures during an end-expiratory occlusion (EEO) yielded total PEEP (PEEP), PesEEO, and PLL. Lung elastance (EL) was calculated as (PLL – PLL)/VT, and chest wall elastance (Ecw) was calculated as (PesEEO – PesEEO)/VT.

**Statistical Analysis**

Data are presented as means ± SD. Linear regression with the coefficient of determination and ANOVA (JMP, SAS Institute) were used as appropriate. Significance was assumed for P < 0.05.

**RESULTS AND DISCUSSION**

The subjects were seriously ill (45), and most were ventilated with a low VT and high PEEP, consistent with current recommendations (1). Table 1 shows subject characteristics, blood gas values, and preintervention ventilator settings.

**Esophageal Pressure**

Pes values were quite high and variable among patients. Whereas pleural pressure inferred from Pes in upright subjects is usually subatmospheric at end exhalation, PesEEO in our patients averaged 18.6 ± 4.7 cmH2O, and PesEEO averaged 22.3 ± 5.0 cmH2O. These PesEEO values are higher than those
of 10 healthy supine subjects at relaxed functional residual capacity (3.3 ± 3.2 cmH2O) (47). They are also higher than the average 8.0 ± 3.1 cmH2O in 10 supine subjects of normal weight without lung disease studied under anesthesia and paralysis during ventilation without PEEP (2a). Several arguments suggest that these high values in patients are consistent with known pathophysiology. First, in the supine posture, Pes is known to overestimate Ppl at midlung height by 3.2 cmH2O in 10 supine subjects of normal weight without lung disease studied under anesthesia and paralysis during ventilation without PEEP (2a). Several arguments suggest that these high values in patients are consistent with known pathophysiology. First, in the supine posture, Pes is known to overestimate Ppl at midlung height by 3.2 cmH2O in 10 supine subjects of normal weight without lung disease studied under anesthesia and paralysis during ventilation without PEEP (2a). Second, abdominal pressure inferred from bladder pressure is variable and greater than normal in many critically ill patients (31, 32), suggesting that Ppl and Pes might also be greater than normal. If the high Pes values we measured reflect real elevations in intrathoracic and pleural pressures, we would expect them to be associated with commensurately high values of Pga and Pblad, which are not subject to the effects of mediastinal weight and inhomogeneous lung mechanics, which are thought to affect Pes in patients. This was, in fact, the case. The average value of end-expiratory Pga was 18.4 ± 5.6 cmH2O, which is greater than the average 5.6 ± 3.8 cmH2O measured in six nonobese patients without lung disease who were anesthetized and ventilated without PEEP before elective surgery (2a). Pblad averaged 19.3 ± 7.8 cmH2O, which is greater than the normal range (~12–15 cmH2O) in subjects in the supine position, with the head of the bed elevated 30° (13). Furthermore, Pga and Pblad were positively correlated with Pes (R² = 0.32, P = 0.0004 and R² = 0.18, P = 0.0104, respectively; Fig. 1), so those patients with higher Pes tended to have higher Pga and Pblad. The similar magnitude and correlation of Pes with Pga and Pblad support the hypothesis that all these measurements reflect a common, variable elevation of pressure within the coelomic cavity in many critically ill patients.

The difference between Pes and Pga in individuals (Pga – Pes) ranged from −9.8 to 8.0 cmH2O and averaged −1.3 ± 4.8 cmH2O (Fig. 2). The Pga-Pes difference is changed in opposite directions by gravitational pressure gradients (13) and transdiaphragmatic pressure. Because the lower esophagus is dorsal to the gastric air bubble, we would expect Pes to be higher than Pga in supine subjects because of the gravitational pressure gradient in the intervening tissues (including that due to the weight of mediastinal contents noted above). On the other hand, passive tension in the diaphragm causes a transdiaphragmatic pressure. We would expect that, in patients with high abdominal pressure, the diaphragm would be stretched, increasing its passive tension and increasing the Pga-Pes difference. This expectation is borne out by the positive correlation of the Pga-Pes difference with Pga, higher Pga values being associated with higher Pga-Pes difference (R² = 0.32, P = 0.0004) and Pblad are positively correlated with Pes (R² = 0.32, P = 0.0004 and R² = 0.18, P = 0.0104, respectively; Fig. 1), so those patients with higher Pes tended to have higher Pga and Pblad. The similar magnitude and correlation of Pes with Pga and Pblad support the hypothesis that all these measurements reflect a common, variable elevation of

Table 1. Subject characteristics and initial ventilator settings

<table>
<thead>
<tr>
<th>Characteristic/Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male gender, %</td>
<td>60</td>
</tr>
<tr>
<td>Age, yr</td>
<td>52 ± 20</td>
</tr>
<tr>
<td>Caucasian, %</td>
<td>88</td>
</tr>
<tr>
<td>Predicted body wt, kg</td>
<td>66 ± 10</td>
</tr>
<tr>
<td>APACHE II on admission, points</td>
<td>26.6 ± 5.6</td>
</tr>
<tr>
<td>Primary physiological injury, %</td>
<td></td>
</tr>
<tr>
<td>Pulmonary</td>
<td>22</td>
</tr>
<tr>
<td>Abdominal pathology</td>
<td>35</td>
</tr>
<tr>
<td>Trauma/blood loss</td>
<td>29</td>
</tr>
<tr>
<td>Sepsis</td>
<td>8</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
</tr>
<tr>
<td>Arterial blood gas analysis at baseline</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>7.33 ± 0.09</td>
</tr>
<tr>
<td>Arterial Pco₂, Torr</td>
<td>41 ± 8</td>
</tr>
<tr>
<td>Arterial Pco₂, Torr</td>
<td>98 ± 38</td>
</tr>
<tr>
<td>Arterial Pco₂-inspiratory O₂ fraction ratio</td>
<td>146 ± 57</td>
</tr>
<tr>
<td>Ventilator settings at baseline</td>
<td></td>
</tr>
<tr>
<td>Inspiratory O₂ fraction</td>
<td>0.70 ± 0.18</td>
</tr>
<tr>
<td>Vt, ml</td>
<td>443 ± 102</td>
</tr>
<tr>
<td>VT/predicted body wt, ml/kg</td>
<td>6.8 ± 1.6</td>
</tr>
<tr>
<td>Respiratory rate, min⁻¹</td>
<td>24.9 ± 6.2</td>
</tr>
<tr>
<td>PEEP, cmH₂O</td>
<td>12.6 ± 4.4</td>
</tr>
<tr>
<td>Pblad, cmH₂O</td>
<td>30.5 ± 6.2</td>
</tr>
</tbody>
</table>

Values are means ± SD. APACHE II, Acute Physiology and Chronic Health Evaluation II; Vt, tidal volume; PEEP, positive end-expiratory pressure; Pblad, plateau pressure.  

Fig. 1. Esophageal pressure at end-expiratory occlusion (Pes) vs. end-expiratory gastric pressure (Pga) in all subjects. Pressures are of similar magnitudes and are correlated. Solid line, line of regression.

Fig. 2. Difference between Pga and Pes (Pga – Pes) vs. Pga, all at end expiration. Dashed line, mean difference; solid horizontal line, line of regression. Pressure difference tended to be greater in atients with higher Pga, suggesting that greater tension in the passive diaphragm had caused greater transdiaphragmatic pressure.
Transpulmonary pressure (PL), which is shown below scans.

PEEP\(_T\) (cmH\(_2\)O), which averaged 15.7 cmH\(_2\)O, is usually substantially less than PEEPT. Solid line, line of regression.

Transpulmonary Pressures at End-Expiratory Occlusion

Because Pes\(_{EEO}\) values were high, the end-expiratory PL,es\(_{EEO}\) values tended to be low, averaging \(-2.8 \pm 4.9\) cmH\(_2\)O, and PL,es\(_{EEO}\) was less than zero in most patients (Fig. 3). PL,es\(_{EEO}\) was much less than the simultaneously measured airway pressure (i.e., PEEP\(_T\)) which averaged 15.7 \pm 4.2\) cmH\(_2\)O.

How could PL,es\(_{EEO}\) reasonably be negative in these patients? Some mechanisms that could affect the relations between PL, PL,es\(_{EEO}\), and PEEPT are depicted in Fig. 4A. First, because Pes is increased in the supine posture by the weight of mediastinal contents (see above), Pes overestimates Ppl at midlung height, and PL,es\(_{EEO}\) underestimates PL by ~5 cmH\(_2\)O. Second, the gravitational gradient in pleural pressure, which would be more important with edematous lungs, could permit the upper (nondependent) lung regions to have a locally positive transpulmonary pressure.

PL is defined as the pressure difference from airway to pleural space, so a negative PL implies that pleural pressure is greater than airway pressure. Note that a negative PL does not imply that the elastic recoil pressure of the lung (alveolar pressure – pleural pressure) is negative; recoil pressure is likely to be positive, even at low lung volume (24). Instead, a negative PL implies that airway closure and/or alveolar flooding have prevented alveolar pressure from equilibrating with airway pressure, and alveolar pressure becomes equal to the local pleural pressure. Airway closure is a normal occurrence in older people at low lung volumes (2, 3), and static negative transpulmonary pressures at very low volumes have been demonstrated in healthy breath-hold divers who have employed glossopharyngeal exsufflation to empty their lungs below residual volume (28). Airway closure probably occurs in all lungs (of terrestrial mammals) that are held at substantially negative transpulmonary pressure (e.g., by application of a highly negative pressure at the trachea). Thus statically negative values of PL are likely when pressures in the thorax and abdomen are pathologically elevated.

PL,es\(_{EEO}\), the difference between PEEP\(_T\) and Pes\(_{EEO}\), is a measure of the pressure distending the lung at end expiration and is controlled clinically by adjustment of PEEP. In our patients, PL,es\(_{EEO}\) was negatively correlated with Pes\(_{EEO}\) (\(R^2 = 0.39, P < 0.0001\)) and positively correlated with PEEP\(_T\) (\(R^2 = 0.21, P = 0.0011;\) Fig. 3), suggesting that the most important determinant of the interindividual differences in PL,es\(_{EEO}\) (and, presumably, also end-expiratory lung volume) was Pes\(_{EEO}\).
which depends on the chest wall, not the PEEP applied by the ventilator.

**Transpulmonary Pressure at End-Inspiratory Occlusion (Plateau)**

As with $PL_{SEEO}$, $PL_{SEEO}$ values were low, averaging $8.3 \pm 6.2$ cmH2O and ranging from $-5.8$ to $26.6$ cmH2O. These values are much lower than the simultaneously measured airway pressures ($P_{plat}$), which averaged $30.5 \pm 6.2$ cmH2O. How could $PL_{SEEO}$ be so low (sometimes less than zero) at end inflation in a critically ill subject? Possible mechanisms are depicted in Fig. 4B. The weight of mediastinal contents lowers $PL_{SEEO}$ relative to $PL$, so $PL_{SEEO}$ could be approximately $-5$ cmH2O without implying a negative effective $PL$. However, even after we accounted for effects of mediastinal weight, many of our estimated static transpulmonary pressures at midlung height ($PL$) are still negative. How could end-inspiratory $PL$ be negative? The gravitational gradient in pleural pressure could permit the upper lung regions to have a locally positive transpulmonary pressure, while the “effective” $PL$ at midlung height remained slightly negative. Furthermore, transpulmonary pressure would be higher during inspiratory flow than during the end-inspiratory occlusion, permitting ventilation, nary pressure would be higher during inspiratory flow than midlung height remained slightly negative. Furthermore, transpulmonary pressure would be higher during inspiratory flow than during the end-inspiratory occlusion, permitting ventilation, even if $PL_{SEEO}$ was negative. These arguments suggest that the range of $PL_{SEEO}$ values in our subjects (after correction for mediastinal weight) could reflect similar values of $PL$.

$PL_{SEEO}$ values were not only positively correlated with $P_{plat}$ ($R^2 = 0.45, P < 0.0001$; Fig. 5) but, also, negatively correlated with $P_{SEEO}$ ($R^2 = 0.18, P = 0.0026$). Thus, although end-inspiratory transpulmonary pressure is largely determined by airway pressure, it is also importantly influenced by the pressure across the chest wall and cannot be adequately predicted from $P_{plat}$ alone.

**Chest Wall Elastance**

Ecw was, on average, slightly greater than normal, $8.7 \pm 4.7$ cmH2O/l, but it ranged widely from 1.3 to $21.8$ cmH2O/l. Perhaps surprisingly, Ecw was not correlated with $P_{SEEO}$, implying that the slope of the pressure-volume curve of the chest wall was not correlated with the position of the curve relative to the pressure axis. Therefore, high levels of Pes at end-expiration are not, in general, associated with high Ecw. Conversely, high Ecw values are not, in general, associated with particularly high levels of $P_{SEEO}$. Ecw was also not correlated with $P_{plat}$ or $PL_{SEEO}$.

**Implications of the Findings for Ventilator Management in ALI/ARDS**

The findings presented above constitute a dilemma. If we maintain that the high Pes values measured in our subjects are artifactual (12, 21), we run the risk of ignoring important information that could be clinically useful (4). In particular, the well-documented elevations in abdominal pressure in some patients with critical illness suggest that there might be similar elevations in pleural pressure that would affect the lungs. Alternatively, if we accept the measured values of Pes and $PL_{es}$ as meaningful, if somewhat flawed, estimates of Ppl and Pt ($after a correction of $\sim 5$ cmH2O), we can use these estimates to assess respiratory mechanics in ARDS/ALI. Below, we consider implications of our findings for management of mechanical ventilation.

**Setting PEEP to set end-expiratory lung volume.** Maintaining inflation of the lungs at end expiration is critical for oxygenation and minimization of atelectrauma (44). Usually, lung inflation at end expiration is adjusted by setting PEEP with the ventilator. However, we found that $PL_{SEEO}$, which depends largely on the pressure across the chest wall, was variable and often substantially lower than the simultaneously measured airway pressure (PEEP$_Y$). It follows that measurement of the pressure across the chest wall ($P_{SEEO}$) and calculation of $PL_{SEEO}$ can help in the choice of an appropriate PEEP in such patients. This strategy was used in our earlier clinical trial (45).

The finding that pleural pressures vary widely among patients implies that the risks and benefits of applied PEEP are likely to vary from patient to patient. A given high level of PEEP in an individual with a high pleural pressure could improve oxygenation and protect the lung from repetitive alveolar collapse, whereas the same level of PEEP in an individual with low pleural pressure could expose the lung to injurious stress at end inspiration. This may account for the difficulty of determining an optimal level of applied PEEP in clinical trials (18). Effects of PEEP on the lungs cannot be fully appreciated without consideration of the effects of the chest wall on transpulmonary pressure.

Ecw and Pes. The chest wall in ARDS has been described as sometimes having low compliance (19). High intrathoracic pressures and low chest wall compliance can be caused by abdominal distension (42). However, high pressures and low compliance need not occur together. Note that elastance, the inverse of compliance, is the change in pressure for a given change in volume and does not predict the pressure at any volume. Our finding that Ecw was not universally elevated is consistent with previous findings in 70 patients with acute respiratory failure (46) and challenges a common perception that high Pes values are due to low chest wall compliance. The state of inflation of the lung depends more on the value of Pes than on the increase in Pes during tidal inflation (elastance). Therefore, the lack of correlation between $P_{SEEO}$ and Ecw underscores the importance of measuring the resting values of

![Fig. 5. Estimated transpulmonary pressure at end-inspiratory occlusion ($PL_{SEEO}$) vs. simultaneously measured airway pressure ($P_{plat}$). $PL_{SEEO}$ is substantially less than $P_{plat}$. Solid line, line of regression.](http://jap.physiology.org/DownloadedFrom)
Pes, not merely the tidal excursions in Pes used to calculate Ecw.

**Lung stress in ALI/ARDS and the effects of the chest wall.** The end-inspiratory airway pressure, $P_{\text{plat}}$, is often used as an index of lung stress during mechanical ventilation and as a means to assess lung injury in ALI/ARDS (1). Checkley et al. (6) recently analyzed preenrollment ventilation parameters in 2,451 patients with ALI/ARDS entered into several of the ARDSNet Trials. They showed that higher preenrollment $P_{\text{plat}}$ values strongly predicted mortality and reasoned that the reciprocal relationship between $P_{\text{plat}}$ and respiratory system compliance suggests that high $P_{\text{plat}}$ and low compliance provide similar information, both indicating lung injury (16). Thus, for a given VT, less compliant lungs would result in a greater increase in airway pressure and higher $P_{\text{plat}}$.

With Pes measurements, it is theoretically possible to measure end-inspiratory lung stress directly. When airways are open and the central airways communicate with alveoli, $P_{L,\text{st}}$ is an estimate of the average end-inspiratory stress of the lung parenchyma (i.e., the elastic recoil pressure of the lung) (34).

In a recent report, Chiumello et al. (7) analyzed the stress applied to the lungs of patients with ALI/ARDS and patients with normal lungs by estimating transpulmonary pressure with an esophageal balloon. However, they equated the end-inspiratory stress applied to the lung with the tidal increase in transpulmonary pressure from that at relaxation volume, discounting the initial (baseline) pressure by subtraction. This approach is common in studies of critically ill patients (14, 19, 30, 35, 41, 42, 48). However, we reasoned that the prestress before inflation might be quantitatively important. For example, the end-inspiratory parenchymal stress after a tidal inflation from a low initial stress (e.g., after inflation from a low lung volume) would be less than that after inflation from a high initial stress (after inflation from a high lung volume), even though the changes in stress might be identical. Similarly, if the lungs were being compressed by a high Ppl at end expiration, the transpulmonary pressure could increase substantially to initiate inflation without causing high end-inspiratory pressures or stress.

With this in mind, we evaluated the possible contribution of prestress to end-inspiratory lung stress in our patients. Parenchymal stress at end inflation can be assessed by measuring the transpulmonary pressure, $P_{L,\text{st}}$, which is the parenchymal stress after inflation, plotted against the 3 parameters that together determine its value. $P_{L,\text{st}}$ is moderately correlated with $P_{L,\text{st}}$ (A), correlated with $E_L$ (B), and not correlated with VT (C).

![Graph A](image1)

![Graph B](image2)

![Graph C](image3)

Fig. 6. Static end-inspiratory transpulmonary pressure ($P_{L,\text{st}} = P_{L,\text{st}} + E_L \times V_T$, where $E_L$ is lung elastance and $V_T$ is tidal volume), which is the parenchymal stress after inflation, plotted against the 3 parameters that together determine its value. $P_{L,\text{st}}$ is moderately correlated with $P_{L,\text{st}}$ (A), correlated with $E_L$ (B), and not correlated with $V_T$ (C).

$P_{L,\text{st}}$ does not account for prestress before inflation and is much greater than $P_{L,\text{st}}$. To assess the contribution of prestress to the estimation of end-inspiratory parenchymal stress, we compared directly measured values of end-inspiratory transpulmonary pressure in our subjects with values calculated using the equation of Chiumello et al. (7): $\Delta P_{\text{stress}} = \Delta P_{\text{aw}} \times E_L / (E_L + E_cw)$, where $\Delta P_{\text{aw}}$ is the tidal increase in airway pressure (i.e., $P_{\text{plat}} - P_{\text{PEEP}}$). The end-inspiratory lung stress calculated by this
equation, which does not account for prestress, averages 22.9 ± 6.5 cmH₂O and ranges from 7.4 to 38.7 cmH₂O, which is much higher than the directly measuredPes.ΔPa, which averaged 8.3 ± 6.2 cmH₂O and ranged from −5.8 to 26.6 cmH₂O (Fig. 7). Even if we assume that Pes is 5 cmH₂O higher than pleural pressure measured at midlung height, as in our earlier clinical trial (45), the two estimates of lung stress differ by 9.6 ± 5.0 cmH₂O. Theoretically, the directly measured end-inspiratory transpulmonary pressure (Pt,s) is a measure of the increase in stress from relaxation volume, which depends only on Es and inflation volume. Thus, ΔPt(stress) provides an incomplete measure of the effects of the chest wall on lung stress.

ACKNOWLEDGMENTS

The authors thank Dr. Frederic G. Hoppin, Jr., for contributions to the revision.

GRANTS

This research was supported in part by National Heart, Lung, and Blood Institute Grant HL-52586.

DISCLOSURES

No conflicts of interest are declared by the author(s).

REFERENCES


