RESEARCH ARTICLE

BAYDUR CORRECTION AND ESOPHAGEAL PRESSURE RELIABILITY

Impact of Baydur Ratio Correction on the Reliability of Esophageal Pressure Measurement

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ABSTRACT

Tidal changes in esophageal pressure (ΔPes) are used as a surrogate for pleural pressure changes (ΔPpl) to assess chest wall mechanics. The Baydur ratio evaluates pressure transmission and guides catheter positioning. The effects of correcting ΔPes using the Baydur ratio on the accuracy of ΔPpl estimation and its dependence on ventilation mode, spontaneous inspiratory effort, and body position, remain unclear. In ten pigs, ΔPpl was measured using intrapleural balloon catheters, while Pes was recorded at three esophageal locations in supine and prone positions. Animals underwent controlled and assisted ventilation. Baydur ratios were derived during assisted ventilation and from external chest compressions during controlled ventilation. ΔPes before and after correction was compared with ΔPpl using mixed-effects models and Bland–Altman analysis. Additionally, we quantified the proportion of values with (ΔPes−ΔPpl) ≤ 1 cmH_2O. During assisted ventilation, ΔPes showed good agreement with posterior ΔPpl. Baydur correction improved scaling and association (slope 0.76 vs 0.50; r 0.81 vs 0.79, $p<0.01$) and increased values within ±1 cmH_2O from 29% to 45% when the Baydur ratio fell outside the accepted range. During controlled ventilation, ΔPes showed weaker association and wider limits of agreement, without improvement after correction. Similar patterns were observed in prone position. ΔPes more accurately reflected posterior ΔPpl during assisted ventilation. Baydur correction improves scaling and association, particularly when the Baydur ratio falls outside the accepted range, but does not improve and may worsen agreement during controlled ventilation.

NEW & NOTEWORTHY

This study shows that the reliability of esophageal pressure as a surrogate of pleural pressure depends on ventilation mode. Using a minimally invasive approach for direct pleural pressure measurement with balloon catheters, we found that Baydur ratio correction improves ΔPes accuracy during assisted ventilation, particularly when the ratio falls outside the accepted range, but not during controlled ventilation.

Keywords: Pleural Pressure; Esophageal Pressure; Mechanical Ventilation; Baydur Test; Respiratory Mechanics.

INTRODUCTION

Accurate partitioning of respiratory system mechanics between lung and chest wall during invasive mechanical ventilation is essential to estimate dynamic lung stress and strain, key determinants of ventilator-induced lung injury (VILI) (1–4). Transpulmonary driving pressure, defined as the tidal variation in transpulmonary pressure, more directly reflects lung stress than metrics based on airway pressure (Paw) and may therefore represent a physiologically meaningful target for lung-protective ventilation strategies (5).

Esophageal pressure (Pes) is a widely used surrogate signal of pleural pressure (Ppl) (6,7). Transpulmonary driving pressure can be estimated from Paw and Pes when static tidal changes in Pes (ΔPes) reliably reflect changes in Ppl (ΔPpl) (8), (9), but this relies on the fidelity with which pressure changes in the pleural cavity are transmitted to the esophageal balloon (10–12). The pressure transmission may be assessed with a Baydur occlusion test in which breathing attempts are made against an occluded airway and the ratio between the resulting swings in Pes and Paw is calculated (13). In spontaneously breathing subjects, a Baydur ratio between 0.8 and 1.2 is generally considered indicative of adequate pressure transmission and is often used to confirm correct catheter positioning and signal quality. Values outside this range prompt reassessment of balloon filling volume and catheter positioning before Pes-derived variables are considered trustworthy (14).

In controlled mechanical ventilation, a modified version of the Baydur test can be applied in which externally applied chest compressions are used to simulate breathing efforts (15,16). Nevertheless, it remains unclear how the Baydur ratio measured in this way compares to that determined during spontaneous respiration, and how it is affected by esophageal balloon location and body position (17). Moreover, it remains unclear whether chest compressions allow ΔPes to be reliably corrected when the Baydur ratio falls outside the accepted range (18). A similar question remains concerning the reliability of correcting for esophageal wall elastance (19). Accordingly, we measured Ppl, Pes and Paw in a mechanically ventilated large animal model to determine a) whether the reliability of ΔPes depends on the presence or absence of inspiratory effort; b) under which conditions Baydur ratio values can be used to improve Pes reliability; and c) whether Baydur ratios obtained during spontaneous breathing can be applied to correct measurements acquired during controlled ventilation. We also explored whether Baydur correction influenced absolute end-expiratory and end-inspiratory pressure estimates relevant for transpulmonary pressure calculation.

MATERIALS AND METHODS

Study design

Ten healthy Yorkshire pigs (30–40 kg) were studied between May and November 2025 after approval by the Institutional Animal Care and Use Committee at Massachusetts General Hospital (Boston, MA).

Animal preparation and ventilation

Pre-anesthesia was achieved with an intramuscular injection of Telazol (4.4 mg/kg), Atropine (0.04 mg/kg), and Xylazine (2.2 mg/kg). Anesthesia was induced with intravenous Fentanyl (2 μg/kg) and Propofol (2 mg/kg). To maintain immobility during imaging and mechanics measurements, an intravenous bolus of Pancuronium (0.1 mg/kg) was delivered followed by endotracheal intubation with a cuffed endotracheal tube. Maintenance of anesthesia consisted of a continuous Propofol infusion (10 mg/kg/h) and supplemental Fentanyl (2 μg/kg every 2 h).

Mechanical ventilation was provided in supine and prone positions with a Servo-I mechanical ventilator (Maquet, Sweden). The fraction of inspired oxygen (FiO_2) was set at 0.4 during all stages of the study.

Esophageal and Pleural pressure catheterizations

Measurement of Ppl (**Figure** 1) and Pes (**Figure S7**) were made using esophageal balloons placed as follows:

- **Pleural catheter:** With the animal supine, the pleural space was identified at the sixth intercostal space in the right anterior axillary line using ultrasound. A 10-cm ultrasound-enhanced Tuohy needle was advanced under ultrasound guidance to puncture the pleural space. An artificial pneumothorax was induced by injecting 150–200 mL of pure oxygen to separate the parietal and visceral pleura. The animal was then turned laterally, and the posterior pleura was accessed in the same intercostal space using CT-guided puncture with a Tuohy needle through the previously induced artificial pneumothorax. Over a guidewire, a 9F sheath was introduced, and a pediatric balloon catheter (Vyaire, US) was positioned for posterior Ppl measurement. After catheter placement, the injected oxygen was manually drained by gentle syringe suction. Then FiO_2 was transiently reduced to 0.21 to facilitate residual pneumothorax reabsorption and subsequently restored to 0.4. The absence of a residual pneumothorax was confirmed by CT scan and a recruitment maneuver.

- **Esophageal catheter:** A balloon catheter (Cooper Surgical, US) was introduced through a 6 mm ET inside the esophagus at three levels in supine (proximal, intermediate, distal; each separated by 5 cm) and two levels in prone (proximal, distal, separated by 10 cm) (**Figure 2**).

The pleural and esophageal catheter balloon positions were evaluated and confirmed by CT scan and direct visual autoptic inspection (Supplementary **Figures S1** and **S2**, respectively). For both balloons, an in vivo pressure–volume (PV) curve was obtained using the Pneumodrive system (Bionica, Brazil) to assess the optimal filling volume thereby minimizing potential measurement errors related to balloon overfilling or underfilling (20).

A dedicated bench validation experiment (Supplementary **Figure S3**) was performed to compare pressure transmission between the pediatric esophageal balloon used for pleural measurements and the adult esophageal balloon catheter. Under controlled conditions, the two balloons showed comparable pressure transmission characteristics, thereby excluding intrinsic differences in balloon mechanics as a source of measurement bias.

Ventilatory protocol

For each esophageal balloon position (Distal, Intermediate, Proximal), the pig was ventilated in both Pressure Support Ventilation and Volume Controlled Ventilation; the ventilator settings for each mode are outlined below.

- **Pressure support ventilation (PSV):** Two PEEP levels (3 and 6 cmH_2O) were used with each of three pressure support levels (2, 8, and 14 cmH_2O). For each of the six PSV settings, after a 2-minute stabilization period, inspiratory and expiratory occlusion maneuvers were performed to obtain static pressure recordings. In addition, six spontaneous inspiratory efforts against an occluded airway valve were obtained, and the Baydur ratio was calculated as the ratio of the negative deflections in Pes and Paw.
- **Volume-controlled ventilation (VCV):** After a recruitment maneuver and neuromuscular blockade, a decremental PEEP trial was performed from 16 to 3 cmH_2O in 2-cmH_2O steps. At each step, during an end-expiratory occlusion, six consecutive manual external chest compressions were delivered over the thorax to generate positive deflection in Paw and Pes, and the Baydur ratio was calculated from the corresponding pressure positive swings. Inspiratory and expiratory holds were performed at each PEEP level while static pressure measurements were taken

Paw, Pes, Ppl, and airway flow signals were continuously recorded at 1000 Hz using LabChart (ADInstruments, New Zealand).

ΔPes and ΔPpl were calculated as the differences between static pressures measured during end-inspiratory and end-expiratory pauses (21). Posterior Ppl was used as the reference standard because Pes reflects local pleural pressure in the mid to dependent mediastinal region and is therefore expected to better reflect dorsal chest wall mechanics (22–24).

Correction of ΔPes

In PSV, because negative Pes swings did not always fully develop and some tracings appeared interrupted or flattened toward end inspiration, swings in Pes and Paw were determined over the first 0.3 seconds of the inspiratory effort (**Figure S7**) (25). This predefined time window was chosen to ensure temporal matching between airway and esophageal pressure changes and to avoid comparing non-synchronous portions of the two pressure tracings. In VCV, Pes and Paw swings were measured from the beginning of inspiration to the maximal positive deflection observed in both Pes and Paw tracings.

For each PEEP step, six consecutive simultaneous ΔPes and ΔPaw swings were measured during the same end-expiratory occlusion maneuver. A Baydur ratio was calculated for each individual inspiratory effort as ΔPes/ΔPaw, and the six breath-by-breath ratios were then averaged to obtain a single mean Baydur ratio for that PEEP step. This resulted in one Baydur ratio for each PEEP level and esophageal catheter position in PSV and one ratio for each step and catheter position of the decremental PEEP trial in VCV. Pes at end-inspiration and end-expiration were corrected by dividing these values by the corresponding mean Baydur ratio, as follows:

Corrected Pes = measured Pes / mean Baydur ratio

We also evaluated whether Baydur ratio correction depends on the presence of respiratory muscle activity during PSV as compared with controlled ventilation. This analysis was restricted to PEEP 3 and 6 cmH_2O to allow direct comparison between ventilation modes, as these PEEP levels were applied in both PSV and VCV modalities. Within these conditions, ΔPes measurements in VCV were corrected not only using the Baydur ratio obtained in VCV, but also using the Baydur ratio measured during PSV at the corresponding PEEP levels and esophageal balloon locations (proximal, intermediate and distal).

Because chest compressions during VCV were performed during end-expiratory occlusion, we assessed the potential presence of airway closure using the Pcond–Pres method (26). This analysis was performed because airway closure could impair pressure transmission between the airway opening and the distal lung compartment during an expiratory hold, thereby affecting interpretation of the chest-compression-derived Baydur ratio. Although low-flow inflation maneuvers were not performed, no evidence of airway closure was detected in the studied animals using the Pcond–Pres approach.

Sample Size Justification

Our preliminary analyses showed a relevant effect of Baydur correction on the accuracy of esophageal pressure–derived estimates of tidal pleural pressure swing (ΔPpl) under the primary experimental condition specified above. Specifically, the absolute error between ΔPes and ΔPpl decreased from approximately 1.75 ± 1.0 cmH_2O for uncorrected values to 0.45 ± 0.6 cmH_2O after Baydur correction.

Because of the crossover design with repeated measurements within each animal, the pig was considered the experimental unit, and observations within the primary condition were summarized within each animal. Based on the paired difference in absolute error (mean reduction ≈ 1.3 cmH_2O, SD ≈ 1.0 cmH_2O), and assuming a two-sided significance level of 0.05 and a power of 0.8, the minimum required sample size was estimated at 5 animals for the experimental crossover study.

Statistical methods

Continuous variables are reported as mean ± SD or median [IQR], as appropriate. Both raw and Baydur-corrected ΔPes were compared with posterior ΔPpl values (considered the reference value)

Association between methods was assessed using linear mixed-effects models with random intercepts per subject to account for repeated measurements, and results were expressed as fixed-effect slopes with 95% confidence intervals. The strength of association was summarized using a correlation coefficient adjusted for repeated measurements. Agreement between methods was evaluated using Bland–Altman analysis adjusted for repeated measurements(27), with bias and limits of agreement accounting for within-subject variability. An a priori threshold of clinical acceptability for agreement was defined as ±1 cmH_2O. For each Bland–Altman analysis, the proportion of observations falling within and outside this predefined range was reported as a percentage of the total number of measurements. For VCV in the supine position at PEEP 3 and 6 cmH_2O, the comparison additionally included ΔPes corrected using Baydur ratios measured during PSV at the corresponding PEEP levels and catheter positions. For stratified analyses, observations obtained during supine VCV and PSV were classified according to the Baydur ratio into an inside accepted range group (0.8–1.2) and an outside accepted range group. This stratification was used to assess the impact of Baydur-based correction under optimal and non-optimal calibration conditions.

Statistical significance was set at $p < 0.05$ (two-tailed). All statistical analyses were performed using Stata (StataCorp, College Station, TX). Graphs were created using GraphPad Prism (GraphPad Software, San Diego, CA).

RESULTS

A total of 541 paired measurements of ΔPes and posterior ΔPpl were obtained from 10 pigs in supine and prone positions, during VCV and PSV, and at three different esophageal catheter positions. Data obtained in the prone position and analyses of absolute pressure values are reported in the Supplementary Material.

Figure 2 shows correlations between ΔPes and ΔPpl measurements obtained in the supine position during PSV (**Panels A, B, C**) and during VCV (**Panel D, E, F**). ΔPes values are displayed with (in red) and without (in black) Baydur correction. During PSV, ΔPes was significantly associated with ΔPpl across all catheter positions. Applying Baydur correction during PSV further strengthened these relationships: regression slopes increased and approached unity and repeated-measures correlation coefficients were higher compared with raw values. During VCV, uncorrected regression slopes were consistently farther from unity compared with those observed during PSV, while repeated-measures correlation coefficients were lower. Furthermore, Baydur correction did not improve correlations with ΔPpl.

Agreement analyses between ΔPes and ΔPpl are shown for PSV (**Figure 3**) and VCV (**Figure 4**). In PSV, Baydur correction (**Figure 3**, **Panels D, E, F**) reduced both bias and limits of agreement compared with the uncorrected ΔPes (**Figure 3**, **Panels A, B, C**) at the proximal and intermediate positions, but not at the distal position, with a higher proportion of observations within ±1 cmH_2O compared with measured values. During

VCV, agreement analysis showed that uncorrected ΔPes values (**Figure 4**, Panels A, B, C) had larger negative biases and wider limits of agreement across positions than in PSV. Baydur correction (**Figure 4**, Panels D, E, F) resulted in reduced biases and a higher proportion of observations within a predefined ±1 cmH_2O range, except in the distal position, but with wider limits of agreement.

Stratification according to the accepted Baydur ratio range (0.8 to 1.2) revealed distinct patterns during PSV. In the unacceptable Baydur group, ΔPes showed lower regression slopes and lower repeated measures correlation coefficients compared with the acceptable group (**Figure S9**). Agreement analyses demonstrated a larger negative bias and wider limits of agreement in this subgroup. Following Baydur correction, slopes increased toward unity, correlation coefficients improved, and both bias and limits of agreement were reduced across catheter positions with a clear increase in the proportion of observations within ±1 cmH_2O (from 29% to 45%) (**Figure S10**). In contrast, during VCV, Baydur correction did not meaningfully change regression or agreement within the acceptable range. In the unacceptable group, Baydur correction was associated with lower slopes, weaker correlations, and wider limits of agreement, while bias was reduced.

Application of Baydur ratios obtained during PSV to correct ΔPes measured during VCV showed differences across catheter positions in regression results. In the intermediate and distal positions, correction using the PSV ratios was associated with higher slopes compared with both raw and corrected ΔPes based on VCV ratios, with the largest difference observed in the distal position (**Figure S11**). Using the same correction, agreement analysis showed narrower limits of agreement in the distal position with similar bias, whereas no consistent improvement in limits of agreement was observed in the proximal and intermediate positions, despite a reduction in bias. This was partially reflected in the proportion of observations within the predefined ±1 cmH_2O range, which was consistently higher across catheter positions (proximal 61% vs 44%, intermediate 50% vs 44%, distal 72%vs 67%) for values corrected using Baydur ratios obtained in PSV compared with ΔPes (**Figure S12**). At matched PEEP levels and catheter positions, PSV and VCV derived Baydur ratios showed weak association within the same animals, with a regression slope of 0.31, r of 0.35, minimal bias (0.04), and wide limits of agreement (−0.37 to 0.45) (**Figure S13)**.

Repeated-measures adjusted regression and Bland–Altman analyses of absolute pressure values are reported in **Table S1**. Baydur-corrected values showed reduced systematic bias compared with raw Pes-derived estimates, particularly for end-expiratory and end-inspiratory pleural pressures. However, regression slopes and R^2 values varied across ventilatory modes and catheter positions, and the reduction in bias was not consistently associated with narrower limits of agreement.

In the prone position, Baydur correction improved both association and agreement between ΔPes and ΔPpl during PSV, whereas no improvement was observed during VCV (**Figures S14-S15**).

DISCUSSION

In this experimental study, we examined the impact of Baydur ratio correction on the reliability of Pes-derived estimates of ΔPpl. We used posterior ΔPpl (**Figure 1**) as the reference because Pes is known to predominantly reflect pressures in the mid to dorsal pleural regions in the supine position (28). Comparisons were performed across ventilation modes, body positions, and esophageal catheter locations (**Figure S7**).

Our main findings can be summarized as follows. First, the reliability of Pes as a surrogate of Ppl depended strongly on the presence or absence of spontaneous inspiratory effort. Second, Baydur correction improved scaling, association and agreement between ΔPes and ΔPpl during PSV, particularly when the Baydur ratio value fell outside the commonly accepted range (0.8-1.2). Third, during controlled ventilation using chest compressions, Baydur correction based on ratios obtained in this ventilation mode did not improve the reliability of Pes. However, when Baydur ratios obtained during spontaneous breathing were applied to controlled ventilation, correction improved association and increased the proportion of observations within a predefined ±1 cmH_2O range compared with raw measurements.

The differences between spontaneous and controlled ventilation are summarized in **Figures 2-4**. During PSV, ΔPes showed stronger coupling with posterior ΔPpl across catheter positions, and Baydur correction further improved scaling and agreement. In contrast, during VCV, the relationship between ΔPes and posterior ΔPpl was weaker and agreement limits remained wider. In this setting, Baydur correction did not consistently improve these relationships and, in some conditions, further reduced slopes or widened limits of agreement. Overall, these findings suggest that Baydur correction should be interpreted according to the ventilation mode and the maneuver used to obtain the Baydur ratio.

Stratification according to the accepted Baydur ratio range further supports this interpretation (**Figures S9 and S10**). During PSV, values outside the accepted range identified conditions in which raw ΔPes was less reliable and Baydur correction was most beneficial. In contrast, during VCV values outside the accepted range did not identify a clearly correctable scaling error, suggesting that Baydur ratios obtained during chest compression may reflect heterogeneous regional pressure transmission rather than a simple mismatch between airway and esophageal pressure swings.

Additional analyses of absolute pressure values showed that Baydur correction often reduced systematic bias between Pes-derived and directly measured pleural pressure values, but did not consistently improve limits of agreement or linear association. This finding supports the interpretation that the Baydur maneuver is more suited to assessing the transmission of pressure swings than to calibrating absolute Pes values.

To further explore whether the breathing condition in which the Baydur ratio is obtained influences its corrective behavior, we applied Baydur ratios measured during PSV to ΔPes obtained during VCV at matched PEEP levels and catheter positions. This approach modified regression slopes (**Figure S11**) and agreement in a position dependent manner. In particular, intermediate and distal positions showed steeper slopes, and narrower limits of agreement in the distal position compared with correction using ratios measured during

VCV (**Figure S12**). The weak agreement between PSV and VCV derived Baydur ratios at matched PEEP and catheter position further supports the concept that Baydur ratios obtained during VCV may not capture the same physiological pressure transmission assessed during spontaneous inspiratory effort.

Analyses performed in the prone position showed a similar pattern, with Baydur correction improving scaling, association and agreement between ΔPes and ΔPpl during PSV but not during VCV (**Figures S14-S15**)

Our findings differ from those reported in prior experimental work by Dechman et al., who observed closer scaling between Pes and Ppl during controlled ventilation in dogs (25). However, in these studies, animals were placed within a plethysmographic chamber, and pressure changes were applied uniformly over the entire thorax. Under such conditions, pressure transmission to the chest wall, pleural space, and lung is spatially homogeneous, favoring consistent coupling between Pes and Ppl. In contrast, in the present study, pressure changes during VCV were generated through external thoracic compressions. Although these compressions were standardized, they remain inherently localized and operator dependent. Pressure transmission under these conditions is influenced by thoracic size, chest wall geometry, and regional mechanics. This likely resulted in heterogeneous transmission of applied forces to the pleural space and esophagus, despite the narrow weight distribution of the animals and relatively homogeneous chest wall compliance of the animals (**Table 1**).

The differential agreement of Baydur-based correction between PSV and VCV may also be explained by the physiological conditions under which the Baydur test was originally developed (13). The Baydur method was first validated in healthy human volunteers during spontaneous breathing, relying on negative pressure swings generated by inspiratory effort. In our study, PSV preserves spontaneous breathing, which may explain why Baydur-based correction consistently improved scaling, association, and agreement in this mode. In contrast, during VCV, Baydur ratios derived from externally imposed positive pressure deflections may not reflect a true scaling mismatch between airway and esophageal pressures. Differences in chest wall distortion between spontaneous breathing and chest compression may limit the applicability of the correction. Moreover, inspiratory muscle activity may generate pressure changes that are physiologically transmitted across the thorax, while external chest compressions may produce a less homogeneus and more localized transmission of pressure.

Moreover, differences in the mechanical conditions between spontaneous and controlled breathing, including distinct diaphragmatic mechanics and regional pressure transmission patterns (29), may explain why Baydur correction more closely reflects physiological pressure transmission during spontaneous breathing than during controlled ventilation and may partly account for the improved performance observed when PSV-derived Baydur ratios are applied during controlled ventilation compared with uncorrected measurements.

The different esophageal balloon locations were intended to mimic the variability in catheter positioning that may occur in clinical practice, where catheter repositioning is recommended when the Baydur ratio falls outside the accepted 0.8–1.2 range (18). Even when the target position is the lower third of the esophagus(30), it is often difficult to ensure correct catheter placement without radiographic imaging (31). Exploring multiple catheter positions generated a range of Baydur ratio values reflecting variability encountered in clinical practice and allowed us to assess its impact on the reliability of Pes measurements (32). Stratification according to whether the Baydur ratio fell inside versus outside the accepted range allowed us to determine if correction could improve ΔPes even when optimal balloon positioning is not feasible in clinical practice.

From a clinical perspective, our results suggest that Pes is more reliable during assisted ventilation than during controlled ventilation. This makes Baydur correction particularly useful during PSV when calibration conditions are suboptimal and the Baydur ratios are outside the accepted range. In contrast, during VCV, neither raw nor corrected ΔPes showed sufficient agreement with ΔPpl.

A particular strength of our study is the use of direct ΔPpl measurement against which to compare ΔPes. Our minimally invasive technique for measuring Ppl allowed evaluation of these relationships using a standard esophageal balloon introduced into the pleural space without disrupting the integrity of the rib cage and the native mechanical properties of the respiratory system. By avoiding an open-chest approach and the need for dedicated pleural pressure sensors, this technique may reduce costs and increase the feasibility of physiological studies requiring direct regional Ppl measurements in animal models. Moreover, confirmation of pleural catheter positioning by CT imaging (**Figure S5**) strengthened the reliability of the reference measurements by ensuring accurate sampling of the dorsal pleural regions, facilitated by the reduced dimensions of the pediatric esophageal balloon used for intrathoracic placement. As reported in the Supplementary Materials (**Figures S1-S4)**, in a bench top study we demonstrated equivalent pressure transmission between pediatric and adult esophageal balloons, supporting the use of pediatric balloons for direct Ppl measurements. Balloon filling volumes for both pleural and esophageal catheters were continuously monitored and periodically adjusted through deflation and reinflation according to the optimal filling volume identified using *in vivo* pressure volume loops (20). However, the absence of simultaneous validation against contralateral pleural measurements or classical wafer-type pleural sensors should be acknowledged when interpreting the regional Ppl data.

Recent evidence suggests that an acceptable Baydur ratio alone does not guarantee reliable esophageal pressure measurement. Wang Xia et al.(33) showed that esophageal balloon catheters introduce dynamic delays and amplitude attenuation even under ideal static conditions, and that model-based correction markedly improved waveform fidelity and derived mechanics. Their findings reinforce the need for complementary correction strategies (such as the Baydur ratio refinement explored in our study) to enhance the reliability of Pes-based assessments during mechanical ventilation.

In contrast, this study has several limitations. First, experiments were conducted in a healthy swine model, with a limited range of chest wall compliance explored, which may not fully capture the regional mechanical heterogeneity, increased Ppl gradients, and airway closure observed in human lung injury. Second, Ppl was measured at a posterior pleural site in only one side of thorax and therefore represents a regional estimate rather than a global average. Given the presence of vertical Ppl gradients, particularly in the supine position, regional differences between assisted and controlled ventilation may influence the relationship between Ppl and Pes. Therefore, differences in the underlying Ppl field between assisted and controlled ventilation could affect the transmission of pressures to the esophagus. Third, although multiple esophageal balloon positions and body postures were explored, experimental conditions were tightly standardized. In particular, balloon inflation volume was carefully controlled using a dedicated pneumatic system to ensure reproducible filling conditions. Such precision in balloon calibration and positioning may be difficult to achieve in routine clinical practice, where variability in inflation volume, signal quality, and patient cooperation can influence Pes measurements. Therefore, the reproducibility of Baydur correction observed in this experimental setting may not directly translate to less controlled clinical environments.

CONCLUSIONS

The accuracy of ΔPes and its agreement with posterior ΔPpl depend strongly on ventilation mode, with a better association in spontaneous inspiratory effort. Baydur-based correction improves scaling, association, and agreement during PSV, particularly under non-optimal calibration conditions, but does not improve and may worsen agreement during VCV. However, applying Baydur ratios obtained during spontaneous breathing to controlled ventilation was associated with improved coupling between ΔPes and ΔPpl compared with uncorrected measurements. These findings underscore the need for ventilation mode specific interpretation of Pes measurements and caution against the indiscriminate application of calibration-based corrections during controlled ventilation. Finally, minimally invasive, image-guided placement of a standard esophageal balloon may provide a feasible approach for direct regional pleural pressure measurement while reducing costs and avoiding open-chest procedures in animal models.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

SUPPLEMENTAL MATERIAL

Supplemental Figs. S1-S15, Table S1.
https://doi.org/10.5281/zenodo.20561240

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DISCLOSURES

The authors declare no conflicts of interest. No disclosures to report.

AUTHOR CONTRIBUTIONS

A.R., Y.X., M.V, E.R., M.B.P.A , J.H.T.B., and M.C. conceived and designed research; A.R., M.D.V, G.M., G.A., E.M., M.V., and M.C. performed experiments; A.R., M.D.V, G.M., S.E.G., Y.X., M.V., J.H.T.B and M.C. analyzed data; A.R., M.V., E.R., J.H.T.B., and M.C. interpreted results of experiments; A.R., G.M., J.H.T.B., and M.C. prepared figures; A.R., G.M., J.H.T.B., and M.C. drafted manuscript; A.R., M.D.V., G.M., T.T.G., D.R.C.,Y.X., M.V., E.R., M.B.P.A., J.H.T.B., M.C., edited and revised the manuscript; A.R., M.D.V., G.M., T.T.G.,G.A., D.R.C., E.M., S.E.G., R.K., R.G., L.B.,Y.X., M.V., E.R., M.B.P.A., J.H.T.B., and M.C. approved final version of manuscript.

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Figure 1: Experimental setup for pleural pressure measurement. Schematic representation of the ultrasound- guided placement of pleural balloon catheter in a swine model. A controlled, transient pneumothorax was induced to allow precise positioning of balloon catheter within the pleural space, followed by pneumothorax resolution and confirmation of correct catheter placement before data acquisition.

Figure 2: Linear regression between ΔPes and posterior ΔPpl in the supine position during PSV (Panel A-C) and VCV (Panel D-F). Uncorrected ΔPes is shown in black, and Baydur-corrected ΔPes is shown in red. Columns represent esophageal catheter position: proximal, intermediate, and distal. Each panel reports the fixed effect slope and repeated measures correlation coefficient (r) derived from linear mixed effects models.

Figure 3: Bland Altman analysis of agreement between ΔPes and ΔPpl in the supine position in PSV mode. Uncorrected ΔPes is shown in black, and Baydur corrected ΔPes in red. Columns represent esophageal catheter position: proximal, intermediate, and distal (from left to right). Bias, limits of agreement adjusted for repeated measurements, and the percentage of observations with absolute difference ($|\Delta Pes - \Delta Ppl|$) $\leq$ 1 cmH_2O are reported in each panel.

Figure 4: Bland Altman analysis of agreement between ΔPes and ΔPpl in the supine position in PSV mode. Uncorrected ΔPes is shown in black, and Baydur corrected ΔPes in red. Columns represent esophageal catheter position: proximal, intermediate, and distal (from left to right). Bias, limits of agreement adjusted for repeated measurements, and the percentage of observations with absolute difference (|ΔPes − ΔPpl|) ≤ 1 cmH_2O are reported in each panel.

Variable	**Value**
Subjects, n	10
Observations, n	541
Body weight, kg (median [IQR])	35 [32–36]

Ventilatory settings – Supine

Variable	**VCV**	**PSV**
Tidal volume, mL (mean ± SD)	321 ± 59	310 ± 120
Tidal volume/kg, mL/kg (mean ± SD)	9.56 ± 1.18	9.41 ± 3.61
Driving pressure, cmH$_2$O (mean ± SD)	10.63 ± 3.69	10.18 ± 3.62

Ventilatory settings – Prone

Variable	**VCV**	**PSV**
Tidal volume, mL (mean ± SD)	320 ± 61	305 ± 123
Tidal volume/kg, mL/kg (mean ± SD)	9.54 ± 1.11	9.28 ± 3.85
Driving pressure, cmH$_2$O (mean ± SD)	9.78 ± 2.77	9.77 ± 3.57

Observations by ventilation mode and catheter position – Supine

Ventilation mode	**Total**	**Proximal**	**Mid**	**Distal**
VCV	172	60	52	60
PSV	150	50	50	50

Observations by ventilation mode and catheter position – Prone

Ventilation mode	**Total**	**Proximal**	**Mid**	**Distal**
VCV	119	60	—	59
PSV	100	50	—	50

Baydur ratio (mean ± SD) – Supine

Ventilation mode	**Proximal**	**Mid**	**Distal**
VCV	0.65 ± 0.22	0.88 ± 0.11	0.95 ± 0.22
PSV	0.70 ± 0.15	0.79 ± 0.14	0.86 ± 0.17

Chest Wall Compliance (median [Q1; Q3]) – Supine

Ventilation mode		**C_{cw} Ppl**	**C_{cw} Pes**	**C_{cw} Pes Corrected**
VCV	Proximal	77.93(56.69;105.82)	130.13(85.88;129.2)	80.34(60.51;104.52)
	Mid	90.89 (67.1; 108.97)	104.7(91.49;133.95)	90.97(80.55;113.55)
	Distal	95.9 (74.2;119.47)	106.78(91.51;139.22)	101.56(75.59;128.32)
PSV	Proximal	77.93(56.69;105.82)	130.13(85.88;129.2)	80.34(60.51;104.52)
	Mid	90.89 (67.1; 108.97)	104.7(91.49;133.95)	90.97(80.55;113.55)
	Distal	95.9 (74.2;119.47)	106.78(91.51;139.22)	101.56(75.59;128.32)

Table 1: Number of subjects and observations are reported together with the distribution of measurements according to body position (supine and prone), ventilation mode (volume-controlled ventilation, VCV; pressure support ventilation, PSV), and esophageal catheter position (proximal, mid, distal), as well as ventilatory settings and Baydur ratio values. Continuous variables are reported as mean ± SD or median [IQR], as appropriate.

1. U/S guided placement of Tuohy needle into pleura

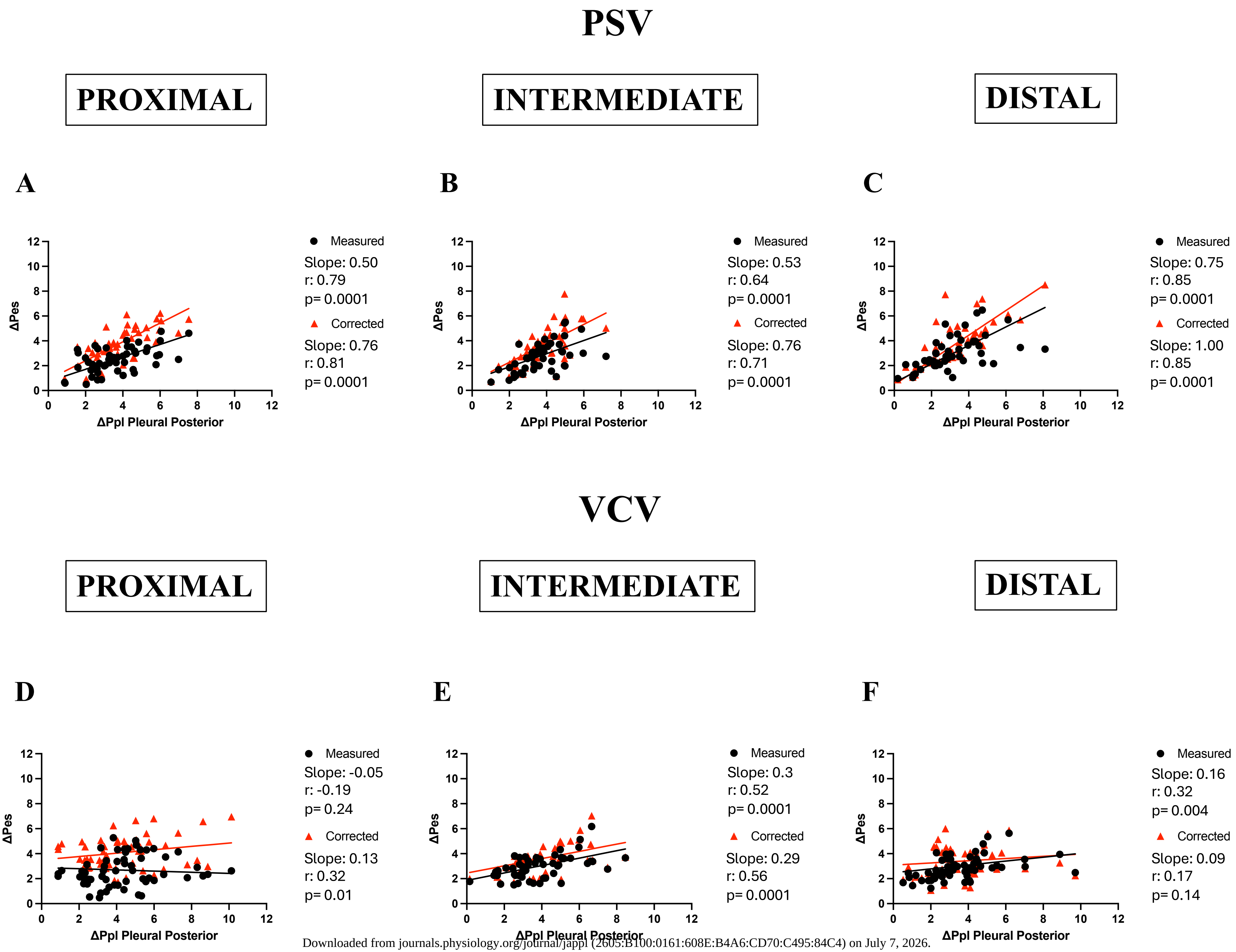
2. Inject 50-200cc of oxygen to induce pneumothorax

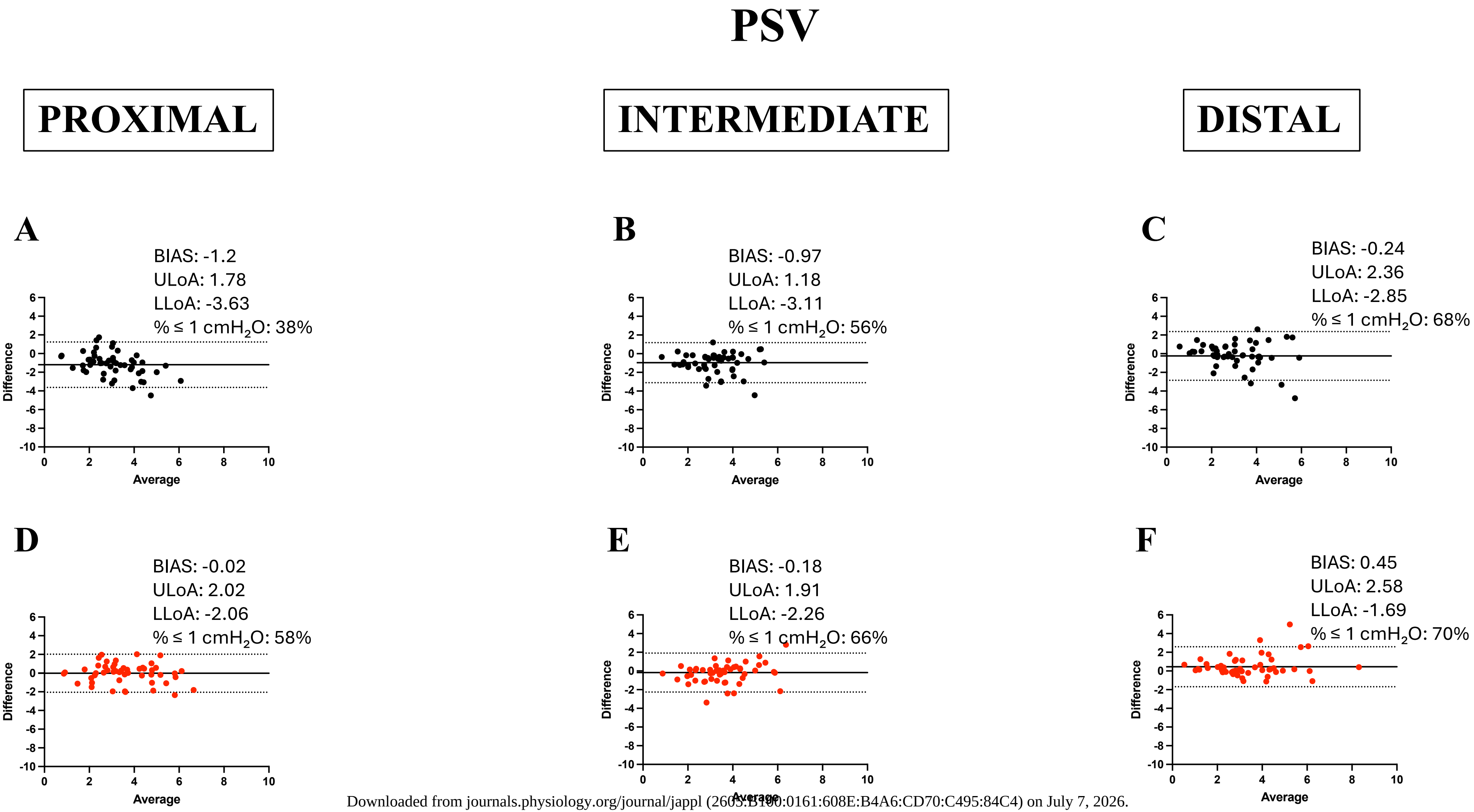
3. Place in semilateral position to allow pneumothorax to drain from dorsal region

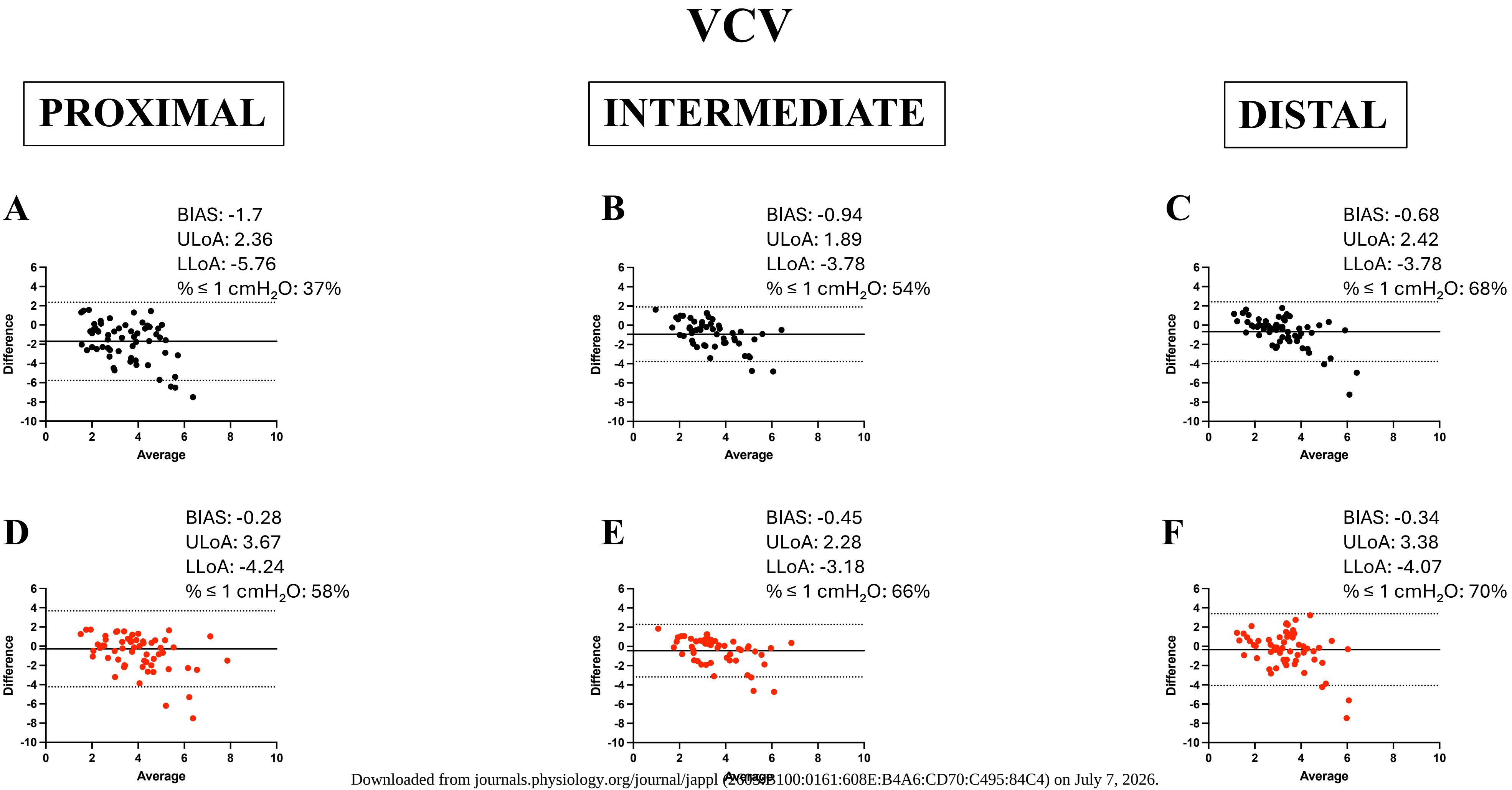
4. Thread guidewire followed by introducer into pleural space

5. Insert pleural catheter into introducer

6. Pronate pig and gently drain pneumothorax. Then, wait for 30 minutes in prone to facilitate complete oxygen absorption


PSV
PROXIMAL
INTERMEDIATE
DISTAL
A
B
C
ΔPes
ΔPpl Pleural Posterior
0
2
4
6
8
10
12
● Measured
Slope: 0.50
r: 0.79
p= 0.0001
▲ Corrected
Slope: 0.76
r: 0.81
p= 0.0001
● Measured
Slope: 0.53
r: 0.64
p= 0.0001
▲ Corrected
Slope: 0.76
r: 0.71
p= 0.0001
● Measured
Slope: 0.75
r: 0.85
p= 0.0001
▲ Corrected
Slope: 1.00
r: 0.85
p= 0.0001
VCV
PROXIMAL
INTERMEDIATE
DISTAL
D
E
F
● Measured
Slope: -0.05
r: -0.19
p= 0.24
▲ Corrected
Slope: 0.13
r: 0.32
p= 0.01
● Measured
Slope: 0.3
r: 0.52
p= 0.0001
▲ Corrected
Slope: 0.29
r: 0.56
p= 0.0001
● Measured
Slope: 0.16
r: 0.32
p= 0.004
▲ Corrected
Slope: 0.09
r: 0.17
p= 0.14


PSV
PROXIMAL
INTERMEDIATE
DISTAL
A
BIAS: -1.2
ULoA: 1.78
LLoA: -3.63
% ≤ 1 cmH$_2$O: 38%
B
BIAS: -0.97
ULoA: 1.18
LLoA: -3.11
% ≤ 1 cmH$_2$O: 56%
C
BIAS: -0.24
ULoA: 2.36
LLoA: -2.85
% ≤ 1 cmH$_2$O: 68%
D
BIAS: -0.02
ULoA: 2.02
LLoA: -2.06
% ≤ 1 cmH$_2$O: 58%
E
BIAS: -0.18
ULoA: 1.91
LLoA: -2.26
% ≤ 1 cmH$_2$O: 66%
F
BIAS: 0.45
ULoA: 2.58
LLoA: -1.69
% ≤ 1 cmH$_2$O: 70%
Difference
6
4
2
0
-2
-4
-6
-8
-10
Average
0
2
4
6
8
10


VCV
PROXIMAL
INTERMEDIATE
DISTAL
A
BIAS: -1.7
ULoA: 2.36
LLoA: -5.76
% ≤ 1 cmH$_2$O: 37%
B
BIAS: -0.94
ULoA: 1.89
LLoA: -3.78
% ≤ 1 cmH$_2$O: 54%
C
BIAS: -0.68
ULoA: 2.42
LLoA: -3.78
% ≤ 1 cmH$_2$O: 68%
D
BIAS: -0.28
ULoA: 3.67
LLoA: -4.24
% ≤ 1 cmH$_2$O: 58%
E
BIAS: -0.45
ULoA: 2.28
LLoA: -3.18
% ≤ 1 cmH$_2$O: 66%
F
BIAS: -0.34
ULoA: 3.38
LLoA: -4.07
% ≤ 1 cmH$_2$O: 70%
Difference
Average
6
4
2
0
-2
-4
-6
-8
-10
0
2
4
6
8
10

GRAPHICAL ABSTRACT

Impact of Baydur Ratio Correction on the Reliability of Esophageal Pressure Measurement

Keywords Pleural Pressure • Esophageal Pressure • Mechanical Ventilation • Baydur Test • Respiratory Mechanics

INTRODUCTION

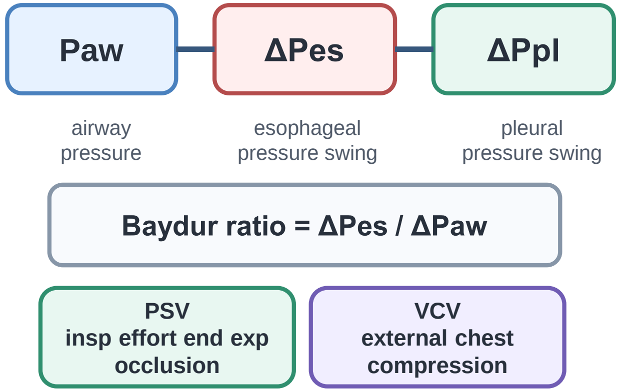
Tidal changes in esophageal pressure (ΔPes) are used to estimate pleural pressure changes (ΔPpl) and chest wall mechanics. Whether Baydur-ratio correction improves ΔPes reliability across ventilation modes remains uncertain.

METHODS

Ten pigs underwent direct posterior pleural pressure measurement using an image-guided intrapleural balloon. Pes was recorded at multiple esophageal locations during PSV and VCV; Baydur ratios were obtained from occluded efforts or chest compressions.

RESULTS / DISCUSSION

During PSV, Baydur correction improved scaling and agreement between ΔPes and ΔPpl, especially when the ratio was outside 0.8–1.2. During VCV, correction did not consistently improve agreement and may worsen it.



Paw
airway pressure

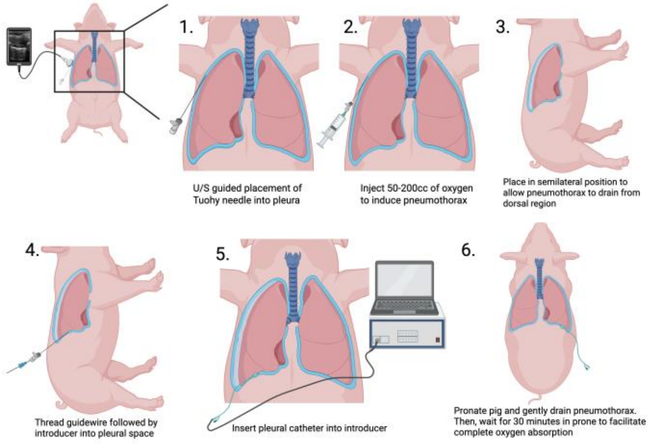
ΔPes
esophageal pressure swing

ΔPpl
pleural pressure swing

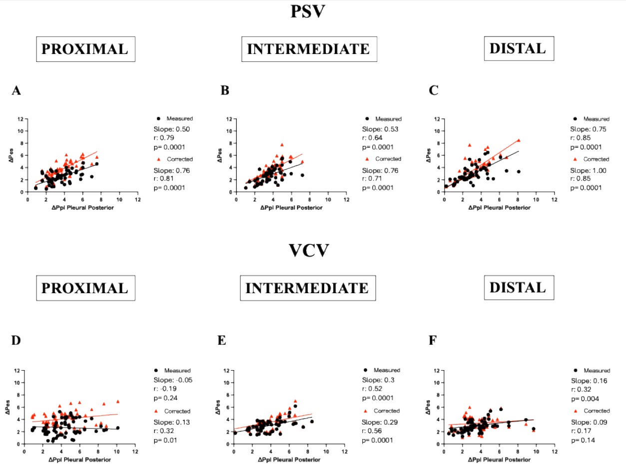
Baydur ratio = ΔPes / ΔPaw

PSV
insp effort end exp occlusion

VCV
external chest compression



1. U/S guided placement of Tuohy needle into pleura
2. Inject 50-200cc of oxygen to induce pneumothorax
3. Place in semilateral position to allow pneumothorax to drain from dorsal region
4. Thread guidewire followed by introducer into pleural space
5. Insert pleural catheter into introducer
6. Pronate pig and gently drain pneumothorax. Then, wait for 30 minutes in prone to facilitate complete oxygen absorption



CONCLUSION Baydur-based correction should be interpreted in a ventilation-mode-specific manner: it appears most useful during assisted ventilation, while indiscriminate application during controlled ventilation should be avoided.