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The Effect of Compartmental Asymmetry on the Monitoring of Pulmonary Mechanics and Lung Volumes

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BACKGROUND: Esophageal pressure measurement for computation of transpulmonary pressure (P_{tp}) has begun to be incorporated into clinical use for evaluating forces across the lungs. Gaps exist in our understanding of how esophageal pressure (and therefore P_{tp}), a value measured at a single site, responds when respiratory system compartments are asymmetrically affected by whole-lung atelectasis or unilateral injury as well as changes in chest wall compliance. We reasoned that P_{tp} would track with aerated volume changes as estimated by functional residual capacity (FRC) and tidal volume. We examined this hypothesis in the setting of asymmetric lungs and changes in intra-abdominal pressure. METHODS: This study was conducted in the animal laboratory of a university-affiliated hospital. Models of unilateral atelectasis and unilateral and bilateral lung injury exposed to intra-abdominal hypertension (IAH) in 10 deeply sedated mechanically ventilated swine. Atelectasis was created by balloon occlusion of the left main bronchus. Unilateral lung injury was induced by saline lavage of isolated right lung. Diffuse lung injury was induced by saline lavage of both lungs. The peritoneum was insufflated with air to create a model of pressure-regulated IAH. We measured esophageal pressures, airway pressures, FRC by gas dilution, and oxygenation. RESULTS: FRC was reduced by IAH in normal lungs ($P < .001$) and both asymmetric lung pathologies ($P < .001$). P_{tp} at end-expiration was decreased by IAH in bilateral ($P = .001$) and unilateral lung injury ($P = .003$) as well as unilateral atelectasis ($P = .019$). In the setting of both lung injury models, end-expiratory P_{tp} showed a moderate correlation in tracking with FRC. CONCLUSIONS: P_{tp} tracks with aerated lung volume in the setting of thoracic asymmetry and changes in intra-abdominal pressure. However, used alone, it cannot distinguish the relative contributions of air-space distention and recruitment of lung units. *Key words: intra-abdominal hypertension; mechanical ventilation; animal model; esophageal pressure; lung injury; functional residual capacity.* [Respir Care 2016;61(11):1536–1542. © 2016 Daedalus Enterprises]

Introduction

In the clinical setting, adjustments of ventilator settings have traditionally relied on monitored airway pressures and tidal volume. Two laboratory methods recently deployed, esophageal pressure (P_{es}) measurement and functional residual capacity (FRC) estimation by gas dilution, have the potential to refine our understanding of the mechanics of the lung itself. Estimation of pleural pressure using P_{es} enables computation of transpulmonary pressure (P_{tp}) and thereby helps separate the contributions of lungs and chest wall to the mechanics of the respiratory system as a whole. However, the individual components of this P_{tp} are sampled from single sites (airway opening and esophagus).

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As a result, P_{tp} does not fully characterize the regional properties of the mechanically heterogeneous lung. For example, even when lung injury is generalized and diffusely distributed, the dependent zones are known to be exposed to different transalveolar pressures than nondependent zones.[1] The average transpulmonary pressure (airway pressure − P_{es}), therefore, gives an incomplete picture of local forces. Moreover, the 2 individual lungs, physically separated by the mediastinum, commonly are neither normal nor symmetrically diseased but are affected in different ways (eg, by unilateral collapse or inflammation). Alterations of chest wall compliance that stem from thoracic or abdominal pathologies complicate assessment further.[2-4]

Conceptually, the integrated respiratory system sampled by the P_{tp} can be viewed as composed of 3 contiguous and partitioned but interdependent regions or compartments: the left hemithorax (left lung within its pleural enclosure), the right hemithorax (right lung within its pleural enclosure), and the infra-diaphragmatic (abdominal) chamber. Major alterations in one or more of these 3 regions with relative sparing of the others may lead to monitoring challenges distinct from those encountered clinically with more symmetrically distributed pathology. Common examples of mechanically asymmetric lung conditions include lobar or whole-lung atelectasis, unilateral aspiration, and pulmonary contusion. The question of how P_{tp} responds to these clinically encountered problems using data (P_{es}) measured from a single site contiguous to lungs with lateralized disease remains unaddressed. Furthermore, we are unaware of experimental or clinical studies that address the consequences of intra-abdominal hypertension (IAH) for P_{tp} when only a single lung is collapsed or injured. In the present experimental study, we explored those specific gaps in our monitoring knowledge.

Due to its central position in the thorax, P_{es} (and therefore P_{tp}) under conditions of compartmental asymmetry might be influenced disproportionately by the mechanical properties of either side. Under such conditions, we could not predict its fidelity in tracking the overall responses of the integrated respiratory system. Using a porcine model, we aimed to (1) characterize the effects of lateral asymmetry of lung mechanics on calculated P_{tp} and (2) explore the impact of IAH on the correspondence between changes of P_{tp} and FRC in the settings of healthy lungs, asymmetric lung conditions (unilateral atelectasis and unilateral lung injury), and symmetrically injured lungs. We examined the hypothesis that P_{tp} would track changes of aerated volume (as estimated by FRC) in the setting of asymmetric lung pathologies and changes of intra-abdominal pressure (IAP).

QUICK LOOK

Current knowledge

Transpulmonary pressure and functional residual capacity have both gained attention as parameters that inform patient care and are measurable at the bedside. Clinical and experimental trials utilizing these measurements have been primarily in the setting of diffuse lung pathology. There is less information on how these parameters respond to thorax asymmetry.

What this paper contributes to our knowledge

There is a moderate correlation between end-expiratory transpulmonary pressure and FRC in the setting of an experimental model of asymmetric lung injury and intra-abdominal hypertension. Our results suggest that for a given subject changes of transpulmonary pressure could prove useful when evaluating changes of aerated volume in clinical settings of respiratory system asymmetry.

Methods

This protocol was approved by the Animal Care and Use Committee of Regions Hospital (St Paul, Minnesota).

Animal Preparation

Young healthy Yorkshire pigs (N = 10, mean weight = 42 ± 5.7 kg) were anesthetized with intramuscular tiletamine hydrochloride and zolazepam hydrochloride/xylazine followed by a continuous infusion of tiletamin hydrochloride and zolazepam hydrochloride, ketamine, and xylazine. If the pig remained spontaneously breathing despite deep sedation and pain control, as determined by bispectral analysis and reflex testing, vecuronium was given in the minimal effective dose needed to eliminate efforts. Monitoring was facilitated by femoral venous and arterial catheters, tracheostomy to monitor the airway pressure and flow, and midline suprapubic cystostomy.

To facilitate reversible manipulation of intra-abdominal pressure, the peritoneal cavity was first accessed by surgical placement of a gas-tight tracheostomy tube (Shiley Trach tube 7, Covidien, Mansfield, Massachusetts). A CPAP circuit was then connected to the abdominal tracheostomy tube and set to either atmospheric pressure or 20 cm H_2O (14.7 mm Hg) during the normal IAP and IAH phases of the protocol, respectively (see below). Our previous experience demonstrated this model to be highly reproducible and reversible, with applied abdominal pressure correlating tightly with bladder pressure.[2-4] In accord with

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our prior experience, FRC and lung mechanics are significantly affected within this IAP range.[2] The upper level of IAP selected simulates the clinical scenario of IAH, defined as an IAP of ≥12 mm Hg.[5]

Using a method consistent with that reported by Talmor et al[6] and following the recommendations provided by the manufacturer, an esophageal balloon catheter (CareFusion, Yorba Linda, California) was passed to a depth of ~40–50 cm from the incisors, and a total of 1.5 mL of air was used in the balloon. After gastric positioning was confirmed by a transient increase in pressure during gentle compression of the abdomen and by gastric content return, the esophageal balloon catheter was withdrawn to a depth of ~30–40 cm to record P_{es}. Cardiac oscillations were clearly observed in all tracings. The pig remained in the supine position for the full duration of the study.

Mechanical Ventilation

Pigs were ventilated using the Engström Carestation (GE Healthcare, Madison, Wisconsin), operated in volume control mode, square wave flow, tidal volume of 10 mL/kg, frequency 15 breaths/min, inspiratory-expiratory ratio of 1:2, PEEP of 1 cm H_2O, no inspiratory pause, and F_{IO_2} 0.5, and titrated to maintain $S_{pO_2} > 90\%$. Airway pressure, flow, and P_{es} were monitored in standard fashion as described previously.[2]

Lung Pathology Models

Unilateral atelectasis was generated by placing an Arndt endobronchial blocker (Cook Medical, Bloomington, Indiana) into the left main bronchus under bronchoscopic guidance. To collapse the left lung, gas was aspirated from its lung port until there was no further return. Unilateral lung injury was generated by using the same Arndt endobronchial blocker to occlude the left main bronchus and isolate the inflated left lung. During a brief period of ventilator disconnection, surfactant washout of the right lung was completed using 0.9% sodium chloride warmed to body temperature, instilled into the endotracheal tube, and then drained by gravity. Lavage was repeated until the arterial oxygen saturation was 90% on F_{IO_2} 1.0. At that point, the lavage was stopped, the endobronchial blocker was removed, and ventilation of both lungs resumed. A representative animal was evaluated by x-ray after induction of the atelectasis and unilateral lung injury models to confirm asymmetry. Diffuse lung injury was created experimentally by saline lavage of both lungs simultaneously as described above for right lung lavage.

Experimental Protocol

We studied 4 conditions in the following sequence: normal lungs, unilateral (left) lung atelectasis, unilateral lung injury (saline lavage of the right lung with unilateral protective block of the left main bronchus), and bilateral saline lavage. Each condition was evaluated in the settings of normal IAP and of IAH, which were applied in random order.

Recruitment maneuvers were performed at the beginning of each step of the protocol using 10 breaths of pressure-controlled ventilation with peak inspiratory pressure of 40 cm H_2O and PEEP of 20 cm H_2O. Because a minimum PEEP of 1 cm H_2O is a technical requirement for measuring FRC when using the Engström Carestation mechanical ventilator, this served as the end-expiratory airway pressure during the protocol.

For each combination of IAP and lung condition, airway plateau pressure and P_{es} were recorded during an end-inspiratory pause of 5 s. End-expiratory P_{es} was similarly recorded. FRC was measured using the washin/washout method available on the CareStation ventilator.[7-9] Heart rate, mean arterial pressure, and arterial oxygen saturation were monitored during the entire experiment. Hemodynamic data and lung mechanics were recorded 5 min after the IAP level had been established and the recruitment maneuver was completed. Arterial blood gases were evaluated 15 min after the recruitment maneuver.

Statistical Analysis

Our dependent variables of interest were (1) EIP_{tp} (the difference between airway pressure and P_{es} at end inspiration), (2) EEP_{tp} (the difference between airway pressure and P_{es} at end expiration), (3) FRC, and (4) P_{aO_2}/F_{IO_2}. The Shapiro-Wilk test was use to assess normality of data.

Each of these variables was described using mean and SD at each combination of the 2 independent variables of the study (lung condition and IAP). Analysis of variance with the Tukey post hoc analysis to adjust for multiple comparisons was performed to assess differences among conditions. The change in dependent variables due to IAH in each condition was evaluated using Student *t* test. The Pearson product-moment correlation coefficient was computed to assess the relationship between EEP_{tp} and FRC.

Results

Functional Residual Capacity

Induction of lung asymmetry models or bilateral lung injury at normal IAP led to similar FRC values, all less than in normal lungs. In the setting of IAH, FRC values for the atelectasis and unilateral lavage models were similar. IAH decreased the FRC of normal lungs, after atelectasis induction, and after unilateral lavage ($P < .001$) when compared with values at normal IAP. In contrast, IAH did not affect FRC in the setting of bilateral lavage (Table 1 and Figs. 1–4A).

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Table 1. Pulmonary Mechanics, Functional Residual Capacity, and Gas Exchange Values in the Setting of Normal Lungs, Unilateral Atelectasis, and Unilateral and Bilateral Lung Pathologies

Studied Conditions	P_{plat} (cm H_2O)	EIP_{tp} (cm H_2O)	EEP_{tp} (cm H_2O)	EIP_{es} (cm H_2O)	EEP_{es} (cm H_2O)	C_{RS} (mL/cm H_2O)	C_{CW} (mL/cm H_2O)	C_L (mL/cm H_2O)	FRC (mL)	P_{aO_2}/F_{IO_2}
Normal lungs										
Normal IAP	12.5 ± 1.7	3.3 ± 1.6	−3.8 ± 0.9	9.2 ± 1.7	4.8 ± 0.9	37.5 ± 9.4	102.6 ± 37.0	61.5 ± 16.5	750 ± 247	479 ± 46
IAH	20 ± 1.4	4.6 ± 2.9	−4.2 ± 1.4	15.5 ± 2.5	5.2 ± 1.4	22.2 ± 3.8	44 ± 16.5	51.0 ± 15.1	560 ± 231	449 ± 45
Unilateral atelectasis										
Normal IAP	18.8 ± 3.7	8.6 ± 2.6	−3.2 ± 2.0	10.2 ± 3.5	4.6 ± 1.4	24.7 ± 6.7	95.9 ± 44.7	37.8 ± 10.6	511 ± 209	272 ± 53
IAH	24.7 ± 3.8	8.8 ± 2.7	−5.3 ± 2.1	16.0 ± 3.2	6.3 ± 2.1	17.3 ± 4.3	44.4 ± 16.1	31.4 ± 8.4	407 ± 178	261 ± 53
Unilateral lung injury										
Normal IAP	19.3 ± 3.1	10.0 ± 3.7	−4.4 ± 0.6	9.3 ± 1.6	5.4 ± 0.6	23.8 ± 4.7	119.1 ± 42.3	30.9 ± 7.1	469 ± 176	146 ± 22
IAH	28.2 ± 2.0	12.6 ± 4.2	−6.0 ± 1.5	15.6 ± 2.8	6.9 ± 1.7	15.6 ± 2.8	55.4 ± 27.1	23.3 ± 4.8	300 ± 129	112 ± 26
Bilateral lung injury										
Normal IAP	23.1 ± 3.2	12.8 ± 3.9	−4.8 ± 0.6	10.3 ± 1.8	5.8 ± 0.6	19.6 ± 14.2	101.6 ± 32.4	25.23 ± 6.7	370 ± 165	77 ± 18
IAH	31.9 ± 3.5	15.3 ± 5.8	−8.4 ± 2.5	16.7 ± 3.6	9.4 ± 2.5	13.9 ± 2.4	69.6 ± 31.3	18.8 ± 5.6	313 ± 125	69 ± 31

Results are mean ± SD.
P_{plat} = airway plateau pressure
EIP_{tp} = end-inspiratory transpulmonary pressure
EEP_{tp} = end-expiratory transpulmonary pressure
EIP_{es} = end-inspiratory esophageal pressure
EEP_{es} = end-expiratory esophageal pressure
C_{RS} = compliance of the respiratory system
C_{CW} = chest wall compliance
C_L = lung compliance
FRC = functional residual capacity
Normal IAP = no intra-abdominal hypertension (intra-abdominal of 0 cm H_2O)
IAH = intra-abdominal hypertension (intra-abdominal pressure of 20 cm H_2O)

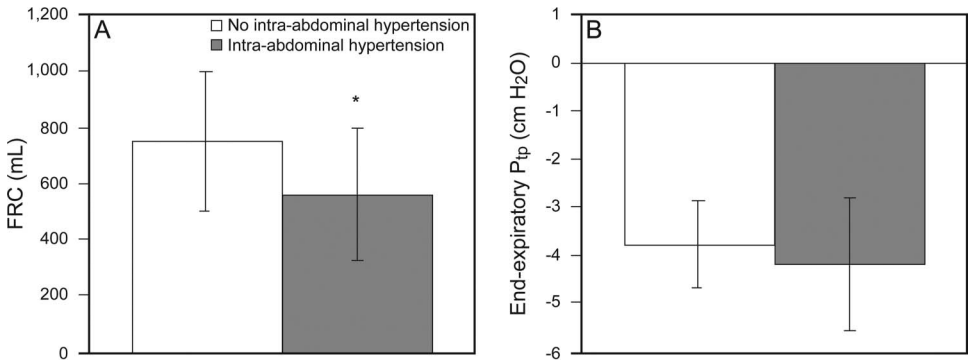

Fig. 1. Functional residual capacity (FRC) and end-expiratory transpulmonary pressure (P_{tp}) in the setting of normal lungs. Induced intra-abdominal hypertension decreased FRC (A). Induced intra-abdominal hypertension did not cause a significant change in end-expiratory P_{tp} (B). Values are shown as mean ± SD. * $P < .001$.

End-Expiratory Transpulmonary Pressure

At normal IAP, EEP_{tp} was statistically similar in normal lungs and in both asymmetric lung conditions. During IAH, EEP_{tp} values were less (more negative) after bilateral injury compared with those for normal lungs ($P = .001$) and both atelectasis model ($P = .005$) (Fig. 2). IAH did not decrease EEP_{tp} in normal lungs. Altering the thoracic compartment, whether via atelectasis ($P = .019$), unilateral lavage ($P = .003$) or bilateral lavage ($P = .001$), resulted in IAH causing a decrease in EEP_{tp} (Table 1 and Figs. 1–4B). In the setting of unilateral and bilateral lung injury models, we found a moderately negative correlation between EEP_{tp} and FRC, with an r value of −.726 ($P < .001$).

End-Inspiratory Transpulmonary Pressure

EIP_{tp} was greater after atelectasis ($P = .003$) and unilateral ($P = .001$) and bilateral lung lavage ($P = .001$) than in normal lungs during normal IAP. Parallel differences were observed in lung injury models during IAH compared with normal lungs ($P = .001$). IAH increased EIP_{tp} relative to

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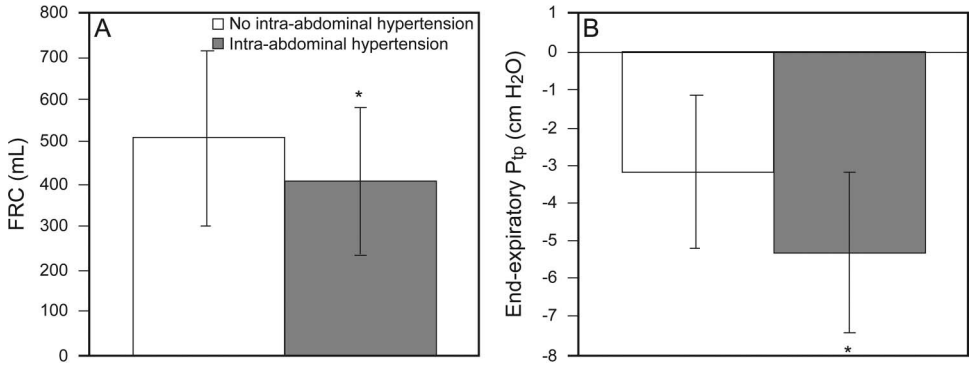

Fig. 2. Functional residual capacity (FRC) and end-expiratory transpulmonary pressure (P_{tp}) in the setting of unilateral atelectasis. Induced intra-abdominal hypertension significantly reduced FRC (* $P < .001$) (A) and end-expiratory P_{tp} (* $P = .019$) (B). Data are shown as mean ± SD.

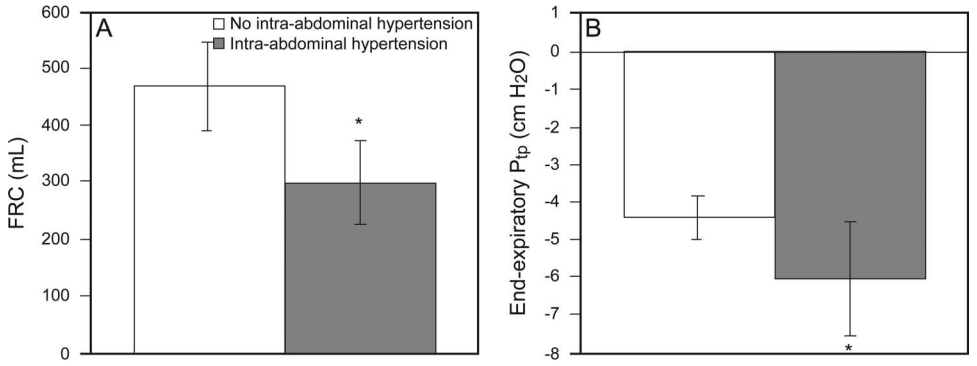

Fig. 3. Functional residual capacity (FRC) and end-expiratory transpulmonary pressure (P_{tp}) in the setting of unilateral lung injury. Induced intra-abdominal hypertension significantly reduced FRC (* $P < .001$) (A) and end-expiratory P_{tp} (* $P = .003$) (B). Data are shown as mean ± SD.

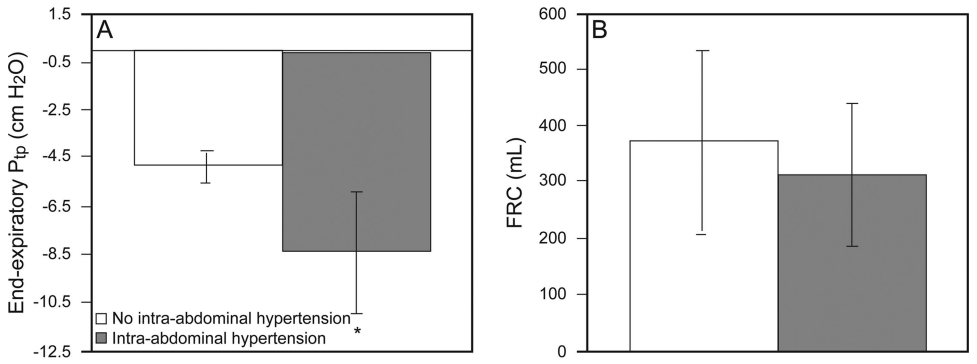

Fig. 4. Functional residual capacity (FRC) and end expiratory transpulmonary pressure (P_{tp}) in the setting of bilateral lung injury. Induced intra-abdominal hypertension significantly reduced end-expiratory P_{tp} ($P = .001$) (A) but did not change FRC (B). Data are shown as mean ± SD.

values at normal IAP for both unilateral ($P = .003$) and bilateral lavage models ($P = .042$) but had no effect on that measurement with normal lungs or atelectasis (Table 1).

Tidal Lung Compliance

Tidal lung compliance (C_L = tidal volume/[EIP_{tp} − EEP_{tp}]) at normal IAP was similar for the asymmetric models but lower for both lung injury models than for normal lungs ($P = .001$). During IAH, these relationships were maintained (Fig. 3). IAH significantly reduced tidal C_L in all models ($P < .001$). (Table 1).

Oxygenation Efficiency

At normal IAP, the P_{aO_2}/F_{IO_2} ratios during atelectasis, unilateral injury, and bilateral injury were significantly lower than for normal lungs ($P = .001$). Each treatment

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condition was significantly different from the others (unilateral vs. bilateral injury $P = .004$; remainder $P = .001$). During IAH, the P_{aO_2}/F_{IO_2} ratios for unilateral and bilateral injury were similar to each other and significantly less than for atelectasis and normal lungs ($P = .001$) (Table 1). IAH decreased P_{aO_2}/F_{IO_2} after unilateral lung injury, compared with its ratio at normal IAP. P_{aO_2}/F_{IO_2} ratios were not affected by IAH in the setting of atelectasis and bilateral lavage (Table 1).

Discussion

The primary findings of our study can be summarized as follows. (1) IAH significantly reduced EEP_{tp} in both asymmetrically and diffusely injured lungs. These changes tracked consistently with measured reductions in FRC. (2) Atelectasis and unilateral lavage were not differentiated from each other by EIP_{tp}, EEP_{tp}, or FRC. In general, changes in P_{tp} were consistent with expected reductions in lung compliance and with measured FRC.

Volume Changes as Interpreted By Transpulmonary Pressure

To our knowledge, our study was the first to approach the question of P_{tp} performance in the setting of lateralized parenchymal disorders. Although the esophageal catheter records pressure from only one site in a mechanically heterogeneous physical environment, our results demonstrate the potential utility of P_{tp} in tracking the aerated space in the setting of laterally asymmetric thoracic compartments.

Changes P_{tp} and FRC may be influenced by compensatory interdependence among the compartments that comprise the respiratory system in this experimental setting. The relative insensitivity of FRC and P_{es} in differentiating the nature and distribution of *lung* pathologies (unilateral atelectasis, unilateral, and bilateral injury) complement data we previously reported regarding asymmetry of the chest wall due to positioning and pleural fluid instillation.[10] Whether the abdomen is normally compliant or the lung is mechanically asymmetric, changes in P_{tp} appear to correspond to mechanical changes occurring in the aerated portion of the lung. It is notable that P_{tp} changed from negative to positive and back again during serial tidal inflations, suggesting recurring cycles of intra-tidal aeration and collapse in these supine pigs, a position that predisposes to atelectasis in this species.[10] These laboratory data seem to support, at least in principle, the suggested clinical use of P_{tp} as a guide to setting open lung PEEP.[11]

Asymmetric Mechanics

The lack of differences in FRC and P_{tp} between the asymmetric models suggests that P_{tp} is tracking the aerated compartments without distinguishing between gas volume resulting from distention of already open units and that resulting from lung unit recruitment. We had anticipated that aspirating all volume from one lung would result in a significant change in esophageal pressure due to volume loss. However, atelectasis caused relatively little change in FRC, possibly due to compensatory recruitment or distention of open aerated lung units in the contralateral lung during the deflationary aspiration. This lack of change in aerated thoracic volume could account for the stability of P_{es}. An alternative but in our view less likely explanation would be that atelectasis in the immediate surroundings of the esophageal pressure balloon blunted its sensitivity to changes in regional pleural pressure.

Although not the primary focus of this work, the variable that differed between the 2 models of lung asymmetry was oxygenation efficiency. After induction of IAH, the P_{aO_2}/F_{IO_2} deteriorated significantly in unilateral lung injury, but IAH did not affect oxygenation in the setting of atelectasis. Given that they shared similar values for FRC, this disparity of oxygenation efficiency between atelectasis and unilateral injury was presumably due to better preserved hypoxic vasoconstriction or to vascular compression that selectively increased vascular resistance in the atelectasis model, leading to relatively efficient ventilation/perfusion matching.

Effect of IAH on Pleural Pressure and FRC

During passive mechanical ventilation of normal lungs, the thorax adapts to IAH by decreasing FRC without increasing end-expiratory P_{es} or affecting EEP_{tp}.[2] Apparently, this adaptability is attenuated or lost when the lungs are abnormal, since, in contrast to normal lungs,[2] atelectasis and both lavage models demonstrated a significant decrease in EEP_{tp} in response to IAH. Because transpulmonary pressure is the distending force applied across the alveolar wall, negative EEP_{tp} indicates greater pressure outside the lung than within and therefore could represent collapse (atelectasis) occurring in the region sampled by the esophageal balloon.

In contrast to our expectations and our data from the 2 unilateral pathology conditions, IAH did *not* significantly reduce aerated lung volume or oxygenation efficiency after bilateral lung injury. Although the EEP_{tp} was decreased significantly by IAH, there was no accompanying decrease in aerated lung volume after both lungs were injured. Given the severity of lung injury, this volume stability may simply reflect that appositional rib flaring, chest wall recoil, and insertional tethering of muscle fibers limited cephalad incursion of the diaphragm, preventing further decrease of FRC as IAP rose. An alternative explanation for the lack of measurable decrease of FRC could be the failure of open lung units to communicate effectively with central

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airways at end expiration. Such gas trapping has been observed in patients with ARDS.[12]

Effect of IAH on Tidal Lung Compliance

The observed decrease in tidal C_L with IAH seems consistent with loss of expandable lung units within the pressure range applied during tidal inflation. Reduction of tidal C_L during IAH in the setting of lung injury has been reported in other experimental models.[11,13,14]

Limitations

Our experiments were designed to elucidate principles of mechanical behavior, not to quantify them precisely. However, as a laboratory-based experimental study of mechanics conducted in supine animals, even the principles indicated by these results clearly cannot be translated to the bedside without reservation. Our IAP model creates a uniform rather than a hydrostatic pressure; although correlation between the gas pressure applied and measured bladder pressure is excellent,[4] the latter may more closely model commonly encountered clinical pathology. These animals were deeply sedated at all times; however, neuromuscular blocking agents were not administered continuously, so there may have been unrecognized respiratory efforts or variability in chest wall compliance due to muscular tone. Our measurements were limited to a single, low level of PEEP and 2 levels of IAP. Differences in chest wall and abdominal compliance between humans and swine are likely and would affect applicability of this laboratory experiment to clinical studies or decisions. The extent of mechanical interdependence among the pulmonary and abdominal compartments is likely to vary with species and to be influenced by structural and pathological differences among the individuals in question. The focus of this work was restricted to mechanics, and we therefore do not intend to make definitive observations regarding hemodynamics or gas exchange.

Conclusions

In this experimental study of P_{tp} measurement during asymmetrically distributed compartmental abnormalities, P_{tp} tracked with aerated lung volume and its response to IAH. However, P_{tp} alone is influenced by lung compliance and cannot distinguish between the relative contributions of pressure-related air space distention and recruitment of lung units. Our results suggest that for a given patient, changes of P_{tp} could prove useful when evaluating changes of aerated volume in clinical settings of respiratory system asymmetry.

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REFERENCES

1. Pelosi P, Goldner M, McKibben A, Adams A, Eccher G, Caironi P, et al. Recruitment and derecruitment during acute respiratory failure: an experimental study. Am J Respir Crit Care Med 2001;164(1):122-130.
2. Cortes-Puentes GA, Gard KE, Adams AB, Faltesek KA, Anderson CP, Dries DJ, Marini JJ. Value and limitations of transpulmonary pressure calculations during intra-abdominal hypertension. Crit Care Med 2013;41(8):1870-1877.
3. Formenti P, Graf J, Cortes GA, Faltesek K, Gard K, Adams AB, et al. Experimental intra-abdominal hypertension attenuates the benefit of positive end-expiratory pressure in ventilating effusion-compressed lungs. Crit Care Med 2012;40(7):2176-2181.
4. Cortes-Puentes GA, Cortes-Puentes LA, Adams AB, Anderson CP, Marini JJ, Dries DJ. Experimental intra-abdominal hypertension influences airway pressure limits for lung protective mechanical ventilation. J Trauma Acute Care Surg 2013;74(6):1468-1473.
5. Malbrain ML, Chiumello D, Pelosi P, Bihari D, Innes R, Ranieri VM, et al. Incidence and prognosis of intra-abdominal hypertension in a mixed population of critically ill patients: a multiple center epidemiological study. Crit Care Med 2005;33(2):315-322.
6. Talmor D, Sarge T, Malhotra A, O'Donnell CR, Ritz R, Lisbon A, et al. Mechanical ventilation guided by esophageal pressure in acute lung injury. N Engl J Med 2008;359(20):2095-2104.
7. Maisch S, Boehm SH, Weismann D, Reissmann H, Beckmann M, Fuellekrug B, et al. Determination of functional residual capacity by oxygen washin-washout: a validation study. Intensive Care Med 2007; 33(5):912-916.
8. Olegård C, Söndergaard S, Houltz E, Lundin S, Stenqvist O. Estimation of functional residual capacity at the bedside using standardized monitoring equipment: a modified nitrogen washout/washin technique requiring a small change in the inspired oxygen fraction. Anesth Analg 2005;101(1):206-212, table of contents.
9. Graf J, Santos A, Dries D, Adams AB, Marini JJ. Agreement between functional residual capacity estimated via automated gas dilution versus via computed tomography in a pleural effusion model. Respir Care 2010;55(11):1464-1468.
10. Cortes-Puentes GA, Gard K, Keenan JC, Adams A, Dries D, Marini JJ. Unilateral mechanical asymmetry: positional effects on lung volumes and transpulmonary pressure. Intensive Care Med Exp 2014; 2(1):4.
11. Regli A, Mahendran R, Fysh ET, Roberts B, Noffsinger B, De Keulenaer BL. Matching positive end-expiratory pressure to intra-abdominal pressure improves oxygenation in a porcine sick lung model of intra-abdominal hypertension. Crit Care 2012;16(5):R208.
12. Koutsoukou A, Armaganidis A, Stavrakaki-Kallergi C, Vassilakopoulos T, Lymberis A, Roussos C, Milic-Emili J. Expiratory flow limitation and intrinsic positive end-expiratory pressure at zero positive end-expiratory pressure in patients with adult respiratory distress syndrome. Am J Respir Crit Care Med 2000;161(5):1590-1596.
13. Quintel M, Pelosi P, Caironi P, Meinhardt JP, Luecke T, Herrmann P. An increase of abdominal pressure increases pulmonary edema in oleic acid-induced lung injury. Am J Respir Crit Care Med 2004; 169(4):534-541.
14. da Silva Almeida JR, Machado FS, Schettino GP, Park M, Azevedo LC. Cardiopulmonary effects of matching positive end-expiratory pressure to abdominal pressure in concomitant abdominal hypertension and acute lung injury. J Trauma 2010;69(2):375-383.