Lung stress and strain calculations in mechanically ventilated patients in the intensive care unit

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Background: Stress and strain are parameters to describe respiratory mechanics during mechanical ventilation. Calculations of stress require invasive and difficult to perform esophageal pressure measurements. The hypothesis of the present study was: Can lung stress be reliably calculated based on non-invasive lung volume measurements, during a decremental Positive end-expiratory pressure (PEEP) trial in mechanically ventilated patients with different diseases?

Methods: Data of 26 pressure-controlled ventilated patients admitted to the ICU with different lung conditions were retrospectively analyzed: 11 coronary artery bypass graft (CABG), 9 neurology, and 6 lung disorders. During a decremental PEEP trial (from 15 to 0 cmH_2O in three steps) end-expiratory lung volume (EELV) measurements were performed at each PEEP step, without interruption of mechanical ventilation. Strain, specific elastance, and stress were calculated for each PEEP level. Elastance was calculated as delta PEEP divided by delta PEEP volume, whereas specific elastance is elastance times the FRC. Stress was calculated as specific elastance times the strain. Global strain was divided into dynamic (tidal volume) and static (PEEP) strain.

Results: Strain calculations based on FRC showed mainly changes in static component, whereas calculations based on EELV showed changes in both the static and dynamic component of strain. Stress calculated from EELV measurements was 24.0 ± 2.7 and 13.1 ± 3.8 cmH_2O in the lung disorder group at 15 and 5 cmH_2O PEEP. For the normal lungs, the stress values were 19.2 ± 3.2 and 10.9 ± 3.3 cmH_2O, respectively. These values are comparable to earlier publications. Specific elastance calculations were comparable in patients with neurologic and lung disorders, and lower in the CABG group due to recruitment in this latter group.

Conclusion: Stress and strain can reliably be calculated at the bedside based on non-invasive EELV measurements during a decremental PEEP trial in patients with different diseases.

Editorial comment: what this article tells us
Stress and strain are important parameters to describe respiratory mechanics during mechanical ventilation. This study tells us that these parameters can be reliably calculated at the bedside using non-invasive lung volume measurements during a decremental PEEP trial in patients with different diseases.

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Introduction

In the field of engineering, stress and strain are frequently used terms to describe the effect of external force acting on a subject. Stress is defined as the internal distribution of forces per unit of area of a specific material by an external force. The resulting change in shape of the material by the stress applied is called strain. In the 1960s, the terms stress and strain were introduced by pulmonary physiologists to describe respiratory mechanics.[1] Lung stress describes the distribution of forces due to PEEP and tidal volume, whereas strain describes the resulting change in lung volume.

Calculations of strain require measurements of functional residual capacity (FRC). Traditional FRC measurements needed tracer gases, and expensive and bulky equipment.[2,3]Olegard et al.[4] devised the nitrogen multiple breath wash-out (NMBW) technique to measure FRC at the bedside without interruption of mechanical ventilation and additional tracer gases. The NMBW method is integrated in a standard ICU ventilator and uses a step change in fraction of inspired oxygen (FiO_2) to calculate FRC. However, lung volume is influenced by the use of PEEP and therefore it is better to speak of EELV.[5]

For the calculation of stress, the specific elastance should be known or transpulmonary pressure measurements are required. Stenqvist et al.[6] recently developed a technique to calculate elastance without the use of transpulmonary pressure measurements by using EELV measurements. They showed[6] that calculating elastance from EELV measurements correlates very well with elastance calculated from esophageal pressure measurements ($r^2 = 0.96$) in patients with moderate or severe respiratory failure. For patients with pulmonary and extrapulmonary Acute Respiratory Distress Syndrome (ARDS), this comparison resulted in a $r^2 = 0.99$. With this knowledge, the elastance can be calculated by dividing the change in PEEP by the change in PEEP volume. However, specific elastance is the elastance normalized for FRC.

The hypothesis of the present study was: Can lung stress be reliably calculated based on non-invasive lung volume measurements, during a decremental PEEP trial in mechanically ventilated patients with different diseases? Therefore, FRC (EELV at ZEEP) and EELV were measured during a decremental PEEP trial, in patients with different lung conditions, and stress and strain were calculated at each PEEP step.

Materials and methods

Study population

Retrospective lung volume data were collected from 26 pressure-controlled mechanically ventilated patients admitted to the intensive care unit (ICU). The data of the included patients have been used earlier and the results are described in two earlier publications.[5,7] Patients were considered eligible for inclusion in this study if lung volume data at zero PEEP (ZEEP) were present, and if they were mechanically ventilated for < 48 h at inclusion to the original study. The local Medical Ethics committee (Medical Ethical Committee Rotterdam. Dr. Molewaterplein 50, 3015 GE Rotterdam, The Netherlands.) approved the study protocol (02 July 2009; permit nr. MEC-2009-222) and informed consent was obtained from the patient or a legal representative. The exclusion criteria were severe hemodynamic instability (arterial pressure below 60 mmHg, active bleeding, or adrenergic agents other than dobutamin required to maintain blood pressure or output), pneumothorax, thoracic deformations, and severe airflow obstruction due to chronic obstructive pulmonary disease (COPD). COPD was defined as forced expiratory volume in 1 s or vital capacity below predicted value minus two standard deviations.

Study protocol and measurements

All patients received pressure-controlled ventilation (PCV) (Engström Carestation, GE Healthcare, Madison, WI, USA) as this is the standard of care in our hospital. The inspiratory pressure above PEEP (Pinsp) was tailored to reach a tidal volume of 8 ± 2 ml/kg predicted body weight, and remained unchanged during the entire PEEP trial. In addition, FiO_2 was set to achieve a PaO_2 of 8–12 kPa. First baseline measurements were performed, after which a recruitment maneuver (RM) was performed using a peak inspiratory pressure (PIP) of 40 cmH_2O

with 20 cmH_2O PEEP for 30–40 s, during which the respiratory cycle continued, to continue gas exchange. A PEEP of 15 cmH_2O was applied for 15 min to achieve a steady-state situation, by means of a stable carbon dioxide volume (VCO_2) signal for at least 10 min. Steady state was based on VCO_2 as this is the main parameter in the formula to calculate EELV,[4] which is integrated in the Engström Care station. The first PEEP level was set to 15 cmH_2O to avoid peak inspiratory pressures above 30 cmH_2O. Thereafter, a decremental PEEP trial was performed from 15 to 0 cmH_2O PEEP in steps of 5 cmH_2O. Each PEEP level was applied for 10–20 min, depending on the hemodynamics and respiratory stability of patient.

Calculation of EELV, FRC, PEEP volume, strain, specific elastance, and stress

We measured EELV using the NMBW technique devised by Olegard et al.[4] The Engström Carestation ventilator is equipped with an integrated COVX module, which delivers data required to calculate EELV. EELV measurements require a step change in FiO_2. EELV is automatically measured twice (wash-out and wash-in) within one procedure, using a FiO_2 step change of 0.2. At each PEEP level, the EELV measurements were repeated. We considered the EELV measurement at ZEEP as the of the lungs FRC.

Strain describes the relation between end-inspiratory volume (i.e., tidal volume + PEEP volume) and FRC, and is calculated using formula (1)[8]:

$$\text{Strain}_{\text{global}} = \frac{V_T + V_{PEEP}}{\text{FRC}} \quad (1)$$

(V_T = tidal volume; V_{PEEP} = difference between EELV and FRC; FRC = EELV measured at ZEEP).

Protti et al.[9] introduced the terms static strain and dynamic strain. Lung tissue deformation due to application of PEEP is called static strain, as the energy is only once applied to the lungs. Tidal ventilation is a dynamic process, as the energy is cyclically applied to the lungs. Therefore, lung deformation due to tidal volume is called dynamic strain.[9] Static strain and dynamic strain are calculated according to the following formulas (2 and 3)[9]:

$$\text{Strain}_{\text{static}} = \frac{V_{PEEP}}{\text{FRC}} \quad (2)$$

$$\text{Strain}_{\text{dynamic}} = \frac{V_T}{\text{FRC}} \quad (3)$$

(V_{PEEP} = difference between EELV and FRC; VT = tidal volume; FRC = EELV measured at ZEEP).

Stress is calculated using the following formula[10]:

$$\text{Stress} = \text{Specific elastance} \times \text{Strain} \quad (4)$$

Elastance was calculated by the formula as proposed by Stenqvist et al.[6]:

$$\text{Elastance} = \frac{\Delta\text{PEEP}}{\Delta V_{PEEP}} \quad (5)$$

$$\text{Specific elastance} = \text{elastance} \times \text{FRC} \quad (6)$$

(V_{PEEP} = VPEEP = difference between EELV and FRC).

For stress calculations, both the strain and specific elastance at a particular PEEP level were used. For example, to calculate stress at a PEEP level of 15 cmH_2O, the strain and specific elastance at that PEEP level were used.

Statistics

Statistical analyses were carried out using SPSS 21 (IBM, Chicago, IL, USA). Unless specified otherwise, the values are stated as mean ± SD. We screened the distribution of our data using the Kolmogorov–Smirnov test for normal distribution and the Brown–Forsythe test for homoscedasticity. If the data appeared to be distributed normally, we applied ANOVA. Otherwise, the analysis was carried out using the independent samples Kruskal–Wallis test. A linear regression model was performed to compare the stress measured by Chiumello et al.[10] with our stress calculations (Graphpad Prism version 5.0; Graphpad Software Inc., San Diego, CA, USA). For all comparisons, $P < 0.05$ was considered to be significant.

Results

The included patients are divided into three groups based on the diseases (Table 1): coronary artery bypass graft (CABG), neurology patients, and lung disorder patients. Patient characteristics are shown in Table 2. The patients were ventilated with a constant pressure amplitude or driving pressure (CABG: 10 ± 2 cmH_2O; neurology: 13 ± 4 cmH_2O; lung disorders: 15 ± 5 cmH_2O) during the entire PEEP trial. The PaO_2/FiO_2 ratio was significantly lower in the lung disorder group compared to both other groups, whereas EELV measured at 5 cmH_2O of PEEP were comparable between the groups. At ZEEP, the FiO_2 was increased in three CABG patients to maintain a PaO_2 between 8 and 12 kPa. The measured baseline EELV was presented as a percentage of predicted supine FRC to estimate the amount of collapsed lung tissue (Table 2), and no significant differences were found between the groups (Table 2). Changes in respiratory parameters during the decremental PEEP trial for each group are shown in Table 3. There were no significant differences in tidal volume during the PEEP trial for each group, except at ZEEP in the CABG and lung disorders group. At 5 and 0 cmH_2O of PEEP, EELV significantly decreased in each group (Table 3). Only in the CABG group, a significant decrease in PaO_2/FiO_2 was seen at 5 and 0 cmH_2O PEEP (Table 3).

Figure 1 represents the global, static, and dynamic strain for each PEEP level based on FRC. The global strain was above 2 only in the CABG group at a PEEP of 15 cmH_2O (Fig. 1). At the three PEEP levels (15, 10, and 5 cmH_2O), global strain in the lung disorder group was significantly higher compared to neurology group (Fig. 1), but global strain in the CABG group was significantly higher compared to the lung disorder group (Fig. 1). Dynamic strain did not change significantly in any of the groups during the decremental PEEP trial, except at ZEEP in the CABG group due to collapse (Fig. 1).

Specific elastance was calculated for each PEEP level and is shown in Figure 2. The lung disorder group and neurology group had comparable specific elastance values, whereas specific elastance was significantly lower in the CABG group at all PEEP levels (Fig. 2).

The stress is shown in Figure 3. At PEEP of 15 cmH_2O, the global stress decreased with each PEEP step in all groups (Fig. 3). Global stress was significantly lower in the CABG group as compared to the neurology and lung disorders groups at all PEEP levels.

Table 1 Disease characterization of the patient groups.

	CABG	NEUROLOGY	Lung disorders
CABG	11		
SAH		7	
Neuro-trauma		2	
Pneumonia			5
Abdominal sepsis			1
N	11	9	6

CABG, coronary artery bypass graft; SAH, sub-arachnoidal hemorrhage; *N*, number of patients.

Table 2 Baseline demographics.

	CABG	Neurology	Lung disorders
N	11	9	6
Age (years)	70 ± 10	54 ± 18*	63 ± 11
Male:Female (*n*)	7:4	6:3	5:1
Heart rate (BPM)	75 ± 15	78 ± 10	84 ± 32
Weight (kg)	78 ± 13	75 ± 10	77 ± 17
PBW (kg)	66 ± 9	71 ± 10	71 ± 8
Height (cm)	172 ± 9	177 ± 9	176 ± 7
BMI	27 ± 4	24 ± 3	25 ± 5
Respiratory rate (BPM)	15 ± 1	16 ± 4	16 ± 2
PEEP (cmH_2O)	5	5	5
PIP (cmH_2O)	15 ± 2	18 ± 4	20 ± 5†
V_{Te} (ml)	559 ± 89	518 ± 46	728 ± 158†‡
V_T/PBW (ml/kg)	8.5 ± 1.1	7.2 ± 1.2*	10.3 ± 1.8‡
EELV (l)	2.49 ± 0.80	2.29 ± 0.49	2.12 ± 0.64
EELV of predicted supine FRC (%)	69.1 ± 28.3	79.4 ± 28.5	64.7 ± 22.6
LIS	1.4 ± 0.4	1.2 ± 1.0	1.8 ± 0.8
PaO_2/FiO_2 ratio (kPa)	40 ± 17	49 ± 4	28 ± 5†‡
FiO_2 (%)	41 ± 2	37 ± 5*	52 ± 13†‡

Differences are considered to be significant if $P < 0.05$. The results are shown as mean ± SD unless otherwise specified. Significant differences are marked as: *CABG vs. neurology; †CABG vs. Lung disorders; ‡Neurology vs. Lung disorders. CAB, coronary artery bypass graft; PBW, predicted body weight; BMI, body mass index; PEEP, positive end-expiratory pressure; PIP, peak inspiratory pressure; V_{Te}, expiratory tidal volume; EELV, end-expiratory lung volume; FRC, functional residual capacity; LIS, lung injury score; FiO_2 Fraction of inspired oxygen.

Table 3 Respiratory parameter during the decremental PEEP trial.

PEEP (cmH_2O)	15	10	5	0
Peak inspiratory pressure (cmH_2O)				
CABG	25 ± 2	20 ± 2*	15 ± 2*	10 ± 2*
Neurology	28 ± 4	22 ± 4*	18 ± 4*	14 ± 5*
Lung disorders	32 ± 4	25 ± 5*	20 ± 5*	15 ± 5*
Delta inspiratory pressure (cmH_2O)				
CABG	10 ± 2	10 ± 2	10 ± 2	10 ± 2
Neurology	13 ± 4	12 ± 4	13 ± 4	14 ± 5
Lung disorders	17 ± 4	15 ± 5	15 ± 5	16 ± 4
Expiratory tidal volume (ml)				
CABG	587 ± 117	613 ± 102	559 ± 89	397 ± 91*
Neurology	509 ± 50	511 ± 53	518 ± 46	509 ± 60
Lung disorders	674 ± 120	701 ± 158	728 ± 158	579 ± 79*
Respiratory elastance (cmH_2O/l)				
CABG	17.5 ± 2.6	16.7 ± 2.2	18.2 ± 2.6	26.2 ± 5.1*
Neurology	26.3 ± 6.9	24.5 ± 7.4	24.8 ± 8.0	27.7 ± 9.1
Lung disorders	26.1 ± 9.5	21.3 ± 8.3	21.0 ± 9.7	26.5 ± 11.5
EELV (l)				
CABG	3.97 ± 0.70	3.35 ± 0.86	2.49 ± 0.80	1.58 ± 0.63*
Neurology	2.91 ± 0.49	2.68 ± 0.47	2.29 ± 0.49	1.83 ± 0.53*
Lung disorders	2.72 ± 0.89	2.52 ± 0.79	2.12 ± 0.64	1.57 ± 0.48*
PEEP volume (l)				
CABG	2.39 ± 0.42	1.77 ± 0.45*	0.91 ± 0.25*	–
Neurology	1.08 ± 0.49	0.84 ± 0.32	0.46 ± 0.22*	–
Lung disorders	1.20 ± 0.37	0.95 ± 0.43	0.55 ± 0.30*	–
PaO_2/FiO_2 (kPa)				
CABG	63 ± 14	61 ± 14	45 ± 14*	27 ± 10*
Neurology	55 ± 10	55 ± 11	54 ± 12	49 ± 13
Lung disorders	37 ± 15	34 ± 11	29 ± 4	24 ± 3
FiO_2 (%)				
CABG	41 ± 2	41 ± 2	41 ± 2	45 ± 8*
Neurology	37 ± 5	37 ± 5	37 ± 5	36 ± 4
Lung disorders	52 ± 13	52 ± 13	52 ± 13	50 ± 6*

Respiratory elastance was calculated as the ratio of delta inspiratory pressure and expiratory tidal volume. End-expiratory lung volume (EELV) at 0 cmH_2O PEEP was considered as functional residual capacity. Fraction of inspired oxygen (FiO_2). Significant differences as compared to 15 cmH_2O PEEP are indicated by *. $P < 0.05$ was considered to be statistically significant.

In addition, we divided the CABG group in patients with and without collapse-prone lungs based on PaO_2/FiO_2 ratio < 40 or > 40 kPa (Fig. 4). In patients with a PaO_2/FiO_2 ratio < 40 kPa (collapse-prone lungs), global strain was significantly higher in CABG patients with a PaO_2/FiO_2 ratio < 40 kPa as compared to CABG patients with P/F ratio > 40 kPa (Fig. 4).

In addition, we calculated the global, static, and dynamic strain for each PEEP level based on EELV to diminish the effect of recruitment (Fig. 5). In contrast to strain calculations based on FRC (Fig. 1), the dynamic strain based on EELV increased at lower PEEP levels (Fig. 5). Dynamic strain was significantly higher in the lung disorder group compared to both other groups at the used PEEP levels (Fig. 5).

Discussion

Specific elastance and strain can easily be calculated at the bedside using the non-invasive FRC measurements technique without interruption of mechanical ventilation, and from these results stress can be calculated without the measurement of esophagus pressure. Calculations of stress and strain based on non-invasive lung volume measurements can be reliably performed

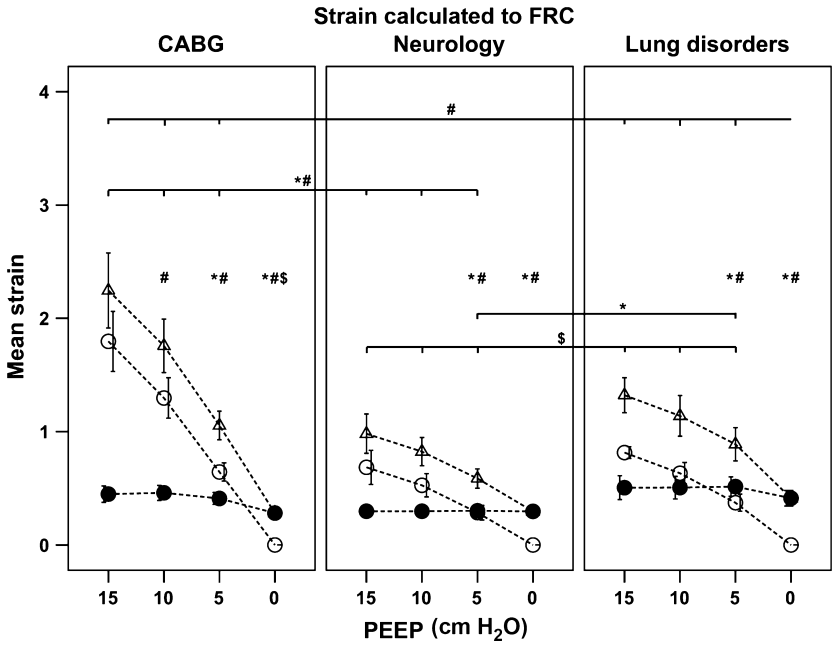

Fig. 1. Strain calculated for patients with different lung conditions during a decremental PEEP trial. Data are shown as mean ± SE. Open triangles: global strain; open circles: static strain (PEEP); closed circles: dynamic strain (tidal volume); dashed lines: interpolation lines. Differences are considered to be significant if $P < 0.05$. *Significant changes in global strain; #Significant changes in static strain; $Significant changes in dynamic strain.

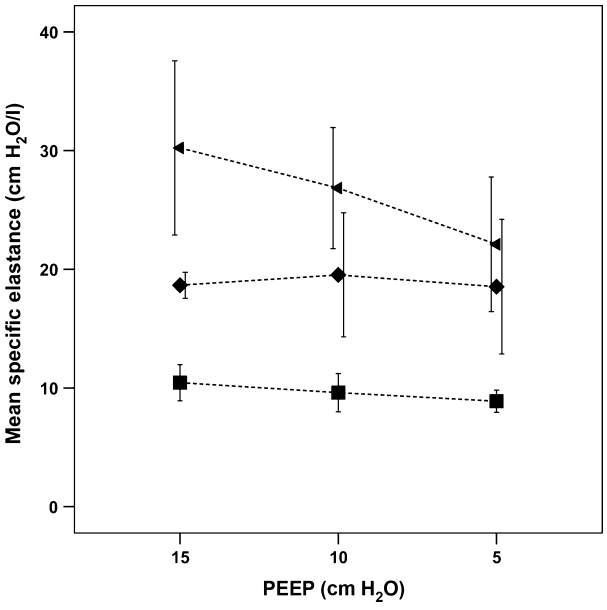

Fig. 2. Calculated specific elastance per PEEP level for each group. Data are shown as mean ± SE. Solid squares: CABG group; Solid arrow: neurology group; Solid diamond: lung disorders group. Data are considered to be significantly different if $P < 0.05$.

during a decremental PEEP trial. Strain has low values in low collapse-prone lungs, whereas high values in high collapse-prone lungs after increasing PEEP. This indicates that recruitability of lung tissue influences strain more compared to collapse of lung tissue.

During mechanical ventilation, external energy is applied to the lung due to tidal ventilation and application of PEEP. This energy is applied to the lung parenchyma creating lung tissue damage, known as ventilator-induced lung injury (VILI). To describe the stress raisers on lung parenchyma, the parameters stress, specific elastance, and strain are introduced (stress = specific elastance x strain). Chiumello et al.[10] calculated lung stress and strain in 80 volume-controlled ventilated patients with and without lung disorders, at four different tidal volumes (6, 8, 10, and 12 ml/kg) and during two different PEEP levels (5 and 15 cmH_2O). EELV was measured using a balloon with helium, and mechanical ventilation was interrupted during each measurement. Stress was calculated based on esophageal pressure

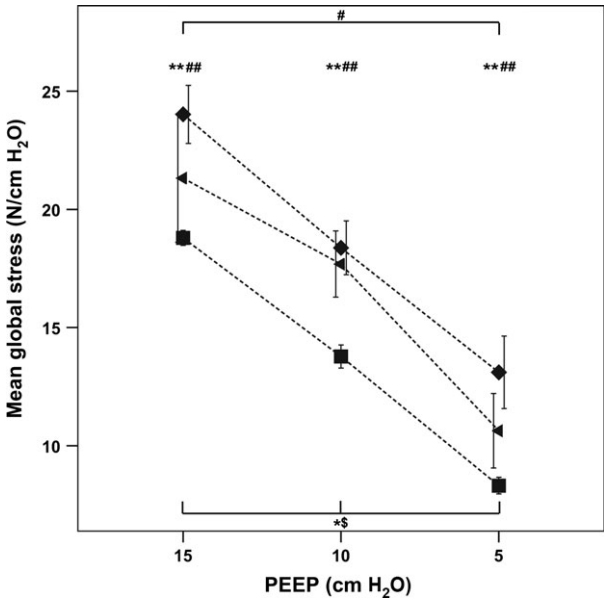

Fig. 3. Changes in global stress during the decremental PEEP trial in the three patient groups. Data are shown as mean ± SE. In both the CABG and lung disorders groups, global stress significantly decreased with each PEEP step, as indicated by * and $, respectively. In the neurology group, global stress only significantly decreased at 5 cmH2O PEEP as compared to 15 cmH2O PEEP, as indicated by #. At all PEEP levels, the global stress was significantly lower in the CABG group as compared to the neurology and lung disorders groups (indicated by ** and ##, respectively). Solid squares: CABG group; Solid arrow: neurology group; Solid diamond: lung disorders group. Data are considered to be significantly different if $P < 0.05$.

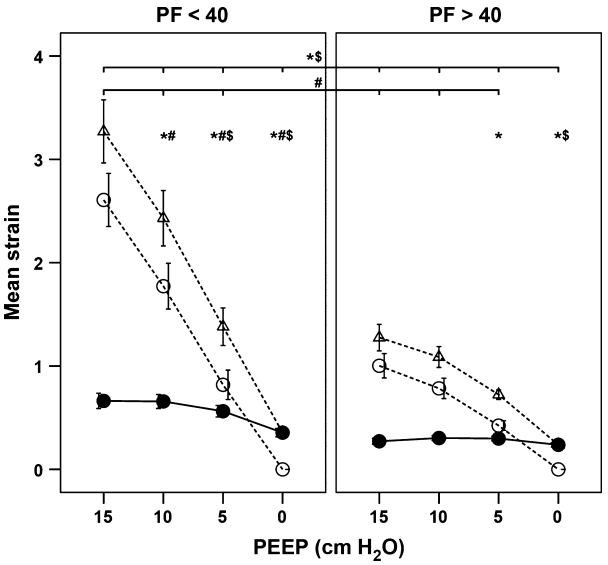

Fig. 4. Changes in strain during a decremental PEEP trial for patients with normal oxygenation or impaired oxygenation within the CABG group. Data are shown as mean ± SE. Strain is calculated for coronary artery bypass graft (CABG) patients with a PaO_2/FiO_2 ratio smaller or larger than 40 kPa. Open triangles: global stress or strain; open circles: static stress or strain (PEEP); closed circles: dynamic stress or strain (tidal volume); dashed lines: interpolation lines. All differences are considered to be significant if $P < 0.05$. *Significant differences in global strain; #Significant differences in static strain; $Significant differences in dynamic strain.

measurements. From both results, specific elastance was calculated and was around 13.5 cmH_2O/l for all patients with and without lung disorders and did not change with tidal volume and PEEP. Our results of specific elastance values were comparable for both the lung disorder and neurology group, whereas not for the CABG group in which specific elastance was around 50% due to recruitability (Fig. 2). Dellamonica et al.[11] calculated lung strain in 30 volume-controlled ventilated patients and found that the static strain was higher in patients with high collapse-prone lungs compared to low recruiters between high and low PEEP. This was also seen in the present study in which global strain was the highest in the CABG patients with a P/F ratio < 40 kPa (Fig. 4).

Gonzalez-Lopez et al.[12] calculated lung strain during volume-controlled mechanical ventilation in 22 patients (16 ALI, 6 controls), without changing ventilator settings. They used EELV instead of FRC and then dynamic strain is only calculated. It was shown that in patients with ALI and a strain > 0.27 resulted in significantly more inflammatory cytokines, measured in bronchoalveolar lavage fluid (BALF). In the present study, patients with lung disorders had a dynamic strain of > 0.27 at all used PEEP levels, but in the CABG and neurology group, dynamic strain was > 0.27 only at ZEEP (Fig. 5). This means that tidal volume is harmful at ZEEP due to the risk of hyperinflation in an atelectatic lung.

Transpulmonary pressure is considered as the main factor of ventilator-induced lung injury. However, measurements of transpulmonary pressure using an esophageal pressure balloon are challenging and therefore a less used technique in daily practice. Therefore, there is a need for an easy to use method to calculate transpulmonary pressure. Recently, Stenqvist et al.[6] proposed a method to calculate transpulmonary pressures based on non-invasive EELV measure-

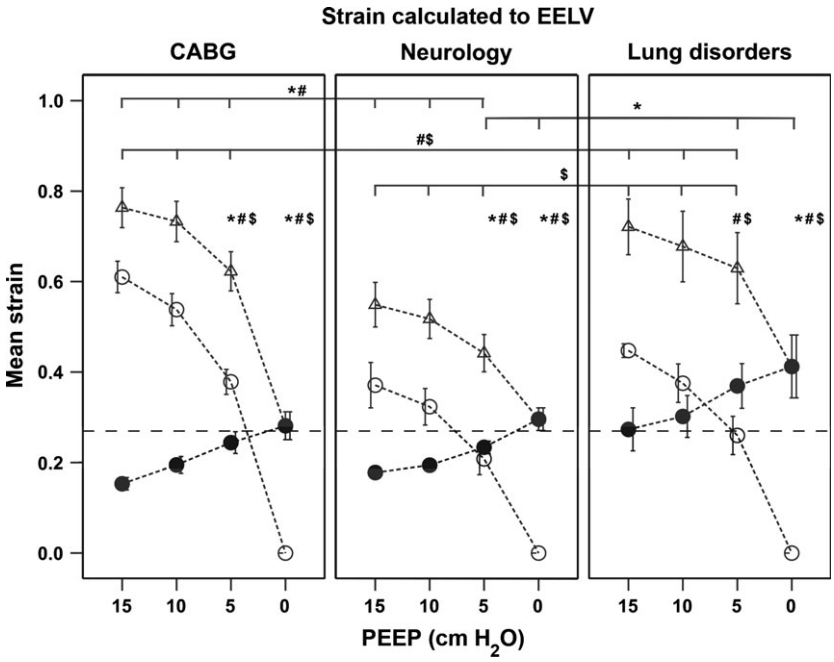

Fig. 5. Strain calculated, based on EELV, for patients with different lung conditions, during a decremental PEEP trial. Data are shown as mean ± SE. The horizontal wide-dashed line represents a threshold strain of 0.27 according the suggestion of Gonzalez-Lopez et al.[12]. Open triangles: global strain; open circles: static strain (PEEP); closed circles: dynamic strain (tidal volume); dashed lines: interpolation lines. Differences are considered to be significant if $P < 0.05$. *Significant changes in global strain; #Significant changes in static strain; $Significant changes in dynamic strain.

ments, during an incremental PEEP trial. They showed in 13 ex vivo pigs that the change in lung volume could be predicted from the change in PEEP divided by lung elastance calculated from esophageal pressure measurements. Therefore, specific elastance could be calculated by multiplying elastance by FRC, in which elastance is calculated as delta PEEP divided by delta EELV. Recently, Lundin et al.[13] confirmed this method in 12 ARDS patients. They calculated elastance from esophageal pressure measurements and the Stenqvist method, and found a close correlation ($r^2 = 0.80$).

In the study of Chiumello et al.[10], it was shown that stress values, based on esophagus pressure measurements, were 21.8 ± 5.4 and 13.3 ± 3.7 cmH_2O at respectively 15 and 5 cmH_2O of PEEP and tidal volume of 10 ml. In the present study, we found 24.0 ± 2.7 and 13.1 ± 3.8 cmH_2O in the lung disorder group at the same PEEP and tidal volume. In addition, Chiumello et al.[10] showed that for patients with normal lungs, the stress values were 19.2 ± 3.2 and 10.9 ± 3.3 cmH_2O at respectively 15 and 5 cmH_2O of PEEP and tidal volume of 8 ml, whereas we found similar values: 21.3 ± 8.1 and 10.6 ± 4.7 cmH_2O at the same PEEP and tidal volume. It is shown that the validity of esophageal pressure measurements as a surrogate for transpulmonary pressure measurements is limited.[14,14–16] Recently, Chiumello et al.[17] compared two different methods to define transpulmonary pressures: directly measured via absolute esophagus pressure and indirectly measured via the ratio of lung elastance and respiratory system elastance. They found that the directly measured esophageal pressure by an esophageal balloon were highly variable between patients and was not related to lung weight, chest wall elastance, and amount of lung collapse. It was concluded that the elastance-derived method to calculate esophageal pressure should be preferred because no disconnection from the ventilator is required and thereby avoiding PEEP loss and derecruitment.

Do the stress and strain calculations have additional information at the bedside for the clinicians to guide ventilation strategies? Stress

increases linearly with the PEEP and the highest values were around 20–25 cmH_2O in the present study. It has been demonstrated that transpulmonary pressures of above 25 cmH_2O are injurious but this is different.[18] Transpulmonary pressure increases during spontaneous breathing due to negative pleural pressure, whereas decreases in patients with stiff chest wall or low lung compliance as seen in patients with ARDS. Therefore, stress calculations do not have additional information compared to transpulmonary pressure. However, the strain calculations based on EELV might be a useful parameter at the bedside to assess ventilator settings. The studies of Protti et al.[9,19] clearly demonstrated that tidal volume is harmful to the lungs, whereas PEEP worked protective. In the present study, we found that dynamic strain (Vt/EELV) calculated on EELV corrects the strain for alveolar recruitment but resulted also in higher values at lower PEEP levels although the inspiratory pressure were the same. The highest values were seen during ZEEP and this is of special interest. During ZEEP, the lung could be collapsed and less alveoli are available to receive tidal ventilation, whereas after recruitment in combination with higher levels of PEEP, higher tidal volume can be applied without damaging the lung. Therefore, we believe that dynamic strain calculations based on EELV could be useful at the bedside but outcome studies are needed to investigate the roll of a strain-guided ventilation protocol.

As we analyzed data of lung volume measurements from earlier studies with a different research question, the study design has some limitations: Firstly, we did not measure esophagus pressures in the present study and compared our data with previous published data.[6,13] Secondly, Stenqvist et al. calculated specific elastance[6] during an incremental PEEP trial, whereas we performed a decremental PEEP trial. In a recent experimental study[20], we performed an incremental and decremental PEEP trial in healthy and ARDS lungs. EELV at ZEEP did not significantly differ between both PEEP trials for both healthy and ARDS lungs. Therefore, in our opinion specific elastance, stress, and strain can be calculated reliably during a decremental PEEP trial. Thirdly, the lung injury group is a relative small group of patients in this study. Finally, we did not use CT or EIT to assess ventilation homogeneity. However, we believe that all techniques used to gather all the information are reliable and suitable for the research goal of the present study.

In conclusion, calculations of specific lung elastance, stress, and strain based on non-invasive lung volume measurements can be reliably done and also during a decremental PEEP trial, in mechanically ventilated patients with different lung conditions. In addition, stress and strain calculations based on EELV should be preferred to correct for lung volume recruitment.

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