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Lung volume and ventilation distribution changes by positioning and application of positive airway pressure in healthy subjects

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Abstract

Background: Noninvasive continuous positive airway pressure (CPAP) is used to improve functional residual capacity (FRC) and ventilation distribution. The aim of this study was to evaluate whether a reduced FRC would be restored by noninvasive CPAP and if this resulted in ventilation distribution changes.
Methods: We investigated 22 subjects. Measurements were made sitting and supine without CPAP and supine with a CPAP of 7cmH2O. FRC was measured with the oxygen washin-washout method. Ventilation distribution was recorded with electrical impedance tomography.
Results: FRC was reduced by 16% from the sitting to the supine position. Ventilation distribution showed a trend to ventral lung regions. In the supine position, application of CPAP increased the FRC but did not change the ventilation distribution.
Conclusion: Noninvasive CPAP restores a reduced FRC in healthy subjects, but does not change ventilation distribution. This may have an impact on the optimization of noninvasive ventilation in patients.

Keywords: Alveolar Recruitment, Electrical Impedance Tomography, Functional Residual Capacity, Lung Volume Measurement, Noninvasive Ventilation, Ventilation Monitoring

Abbreviations and Symbols

α	Type I error
β	Type II error
cmH_2O	centimetres water
CPAP	continuous positive airway pressure
EIT	electrical impedance tomography
FRC	functional residual capacity
NIV	noninvasive ventilation
P	probability
pO_2	partial oxygen pressure
P1-3	body positions studied, see figure 1
Vs	Versus

Introduction

Noninvasive ventilation (NIV) in the treatment of acute respiratory failure has gained increasing popularity in the past three decades. In accordance to the current guidelines, it is the first line treatment for a majority of patients presenting with acute respiratory failure [1, 2].

The treatment can consist of the administration of continuous positive airway pressure alone (CPAP) or of alternating bilevel positive airway pressures (BIPAP). The CPAP offloads intrinsic PEEP and therefore reduces work of breathing. It also leads to recruitment of atelectatic lung regions, thus augmenting alveolar ventilation [3]. Recruitment can be measured as an increase in functional residual capacity (FRC) and as a change in ventilation distribution [4]. While a CPAP which is chosen too low will not efficiently reduce the work of breathing and recruit atelectatic lung regions, an excessive CPAP might induce ventilator associated lung injury. Therefore, it would be helpful for the clinician to estimate the effect of noninvasive ventilation and the applied CPAP on the individual patient´s respiratory system. Measurement of the functional residual capacity (FRC) does not give information about actual recruitment vs. hyperinflation of already aerated lung areas. Regional information on lung aeration can be gathered with electrical impedance tomography (EIT) [5, 6]. Yet, the technique cannot estimate changes of the FRC so far [7]. While EIT is very well validated for invasively ventilated patients, it is not yet clear if ventilation redistributions can be seen when CPAP is administered noninvasively.

We hypothesize that when a reduced FRC is restored by noninvasive application of CPAP, ventilation redistribution can be seen with EIT. The aim of our study was to evaluate the changes of ventilation distribution after restoration of a reduced FRC under the conditions of noninvasive ventilation.

Methods

The study has been approved by the local ethical committee and was conducted at the University Hospital of Luebeck. Having given informed consent, 22 healthy volunteers were studied. The volunteers were kind colleagues and friends of the authors. Two of them had breathed on a ventilator for study reasons before. Inclusion criteria were age over 18 years and having given informed consent. Exclusion criteria were chronic lung conditions requiring chronic, frequent or current medication. Demographic data are displayed in table 1. The volunteers were connected to a ventilator (Evita XL, Draeger Medical, Luebeck, Germany) via a standard face mask (Intersurgical, Wokingham, United Kingdom). The ventilator was set to CPAP mode without pressure support. FRC was determined with the oxygen washin/washout method (LUFU, Draeger-Medical, Luebeck, Germany) in a sitting position without CPAP (P1), in a supine position without CPAP (P2) and in a supine position with CPAP of 7 cmH_2O (P3). See figure 1 for an outline of the study protocol. The sequence of body positions was randomized by throwing a dice. The observer was not blinded to the sequence of measurements. Each measurement took 6 to twelve minutes, depending on the volunteer´s minute volume and FRC. The volunteers stayed connected to the breathing circuit throughout the measurements. Measurements were started once the volunteer´s breathing pattern was calm and regular after change of body positions. Regional ventilation distribution was determined throughout all body positions with electrical impedance tomography (EIT Evaluation Kit II, Draeger Medical, Luebeck, Germany).

Table 1: Demographic data

Gender (female/male)	11/11
Age (years)	31±7
Smoker/non smoker	4/18
Height (cm)	177 ± 8
Weight (kg)	75 ± 11
Body Mass Index (kg/m^2)	24 ± 2.8

Measurement of Functional Residual Capacity

The LUFU System estimates the FRC by oxygen washin/washout, which is a variant of the nitrogen washout method. The technical details have been published before [8]. In

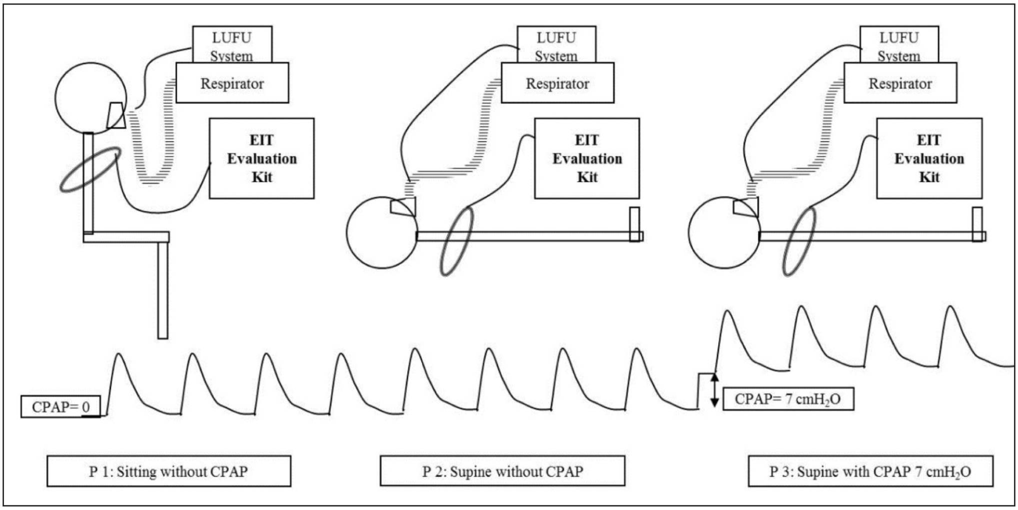

Figure 1: Outline of the study protocol (CPAP: continuous positive airway pressure, EIT: Electrical impedance tomography, P1-3: body positions studied)

brief, a side stream oxygen sensor measures end inspiratory and end expiratory oxygen fractions after a step change of the inspiratory oxygen fraction. A mathematical model allows the calculation of the FRC using the obtained data and volumetric and gas flow data registered by the ventilator. FRC was measured twice, in the oxygen washin and in the washout. The mean of both measurements was used for statistical analysis. One washin/washout cycle lasts approximately 6-12 minutes.

Determination of Ventilation Distribution

EIT was conducted with the EIT Evaluation Kit II (Draeger Medical, Luebeck, Germany). The technique has been introduced in detail before [9]. Electrical impedance tomography bases on measurements of surface potentials after injection of small alternating currents over surface electrode pairs placed equidistant in the circumference of the studied object. Since absolute impedances are very

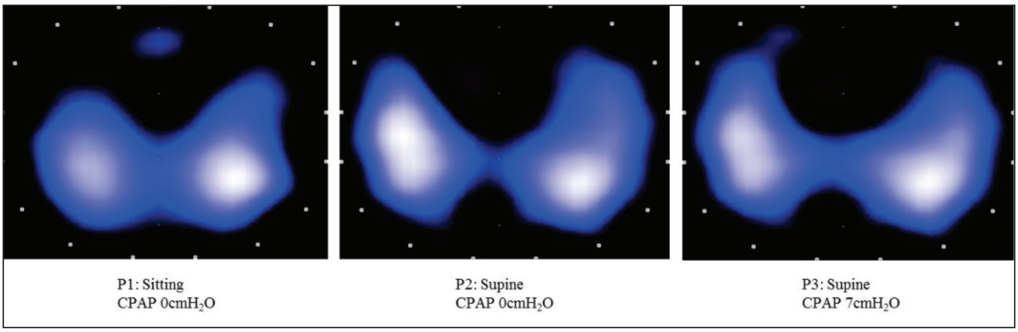

Figure 2: EIT pictures (Dynamic image in full inspiration) of a volunteer in the three positions studied. The picture has to be interpreted like other tomographic images: The upper part of the picture represents the ventral part of the body, the lower parts the dorsal body area. The left side of the picture represents the right side, the right side of the picture the left side of the patient. (CPAP: continuous positive airway pressure, P1-3: body positions studied, see Figure 1)

variable, all measurements are related to a reference measurement. In this study, a silicone belt carrying 16 surface electrodes was placed around the chest at the height of the 5th to 6th intercostal space. A reference electrode was placed approximately 10 cm below the belt on the abdomen. The system displays the impedance changes pixel wise in color code (see Figure 2 for example pictures of a volunteer). Quantitative analysis is possible offline for separate regions of interest. We chose a ventral and dorsal region of interest that represented the ventral and dorsal half of the thorax. In this study, ventilation distribution was recorded for the time of the FRC measurements in each body position. Offline analysis consisted in extracting the tidal variation of thoracic impedance for the whole thorax and for the ventral and dorsal regions of interest separately. Tidal variation is defined as the difference of end inspiratory and end expiratory thoracic impedance and regarded as a representation of tidal ventilation. Regional tidal variation was computed as a fraction of global thoracic impedance variation for ventral and dorsal lung regions. For statistical analysis, the mean of the tidal variations of all breaths taken during FRC measurement was used.

Statistical analysis

Preliminary sample size calculation with data from previous studies [10, 11] revealed a minimum sample size of 20 to detect FRC changes of 25% between the sitting and the supine positions with $\alpha = 5\%$ and $\beta = 80\%$. Normal distribution was checked for with the Kolmogorov Smirnov test. Paired difference analysis was carried out for FRC and tidal variation of impedance between the body positions. Data are presented as mean $\pm$ 1 standard deviation.

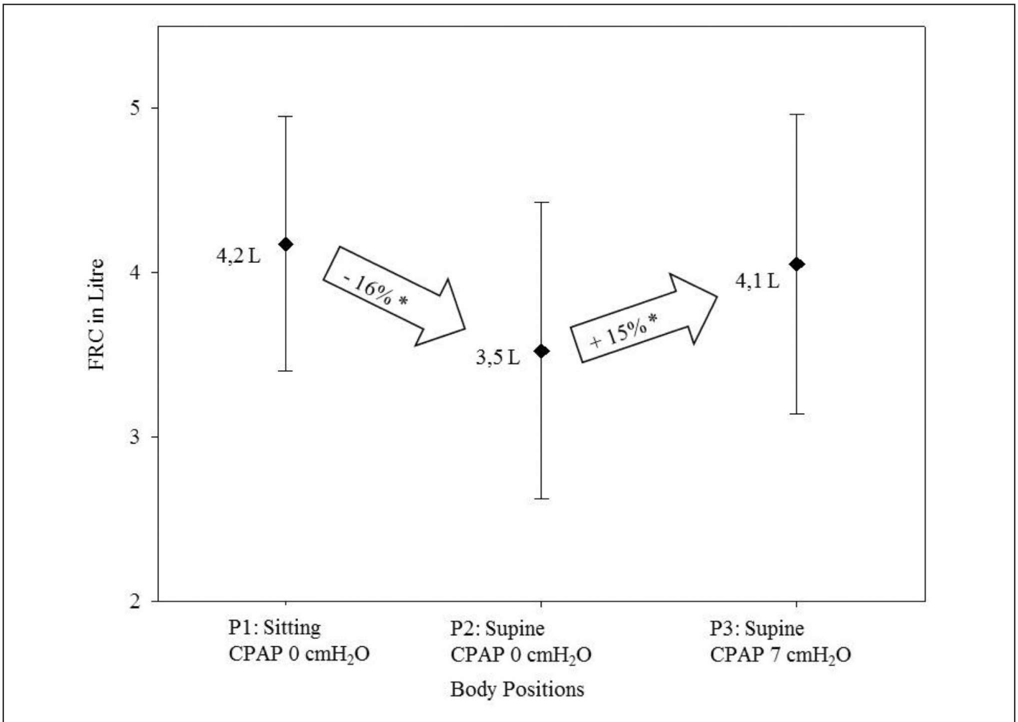

Figure 3: Changes of FRC. Values are means ± 1 standard deviation (CPAP: continuous positive airway pressure, P1-3 body positions studied, see figure 1)

Results

The results for the FRC and tidal variation were normally distributed ($p = 0.61$ and $p = 0.99$, respectively). The change of body position from sitting to supine (P1 to P2) resulted in a decrease of the FRC by 16% ±12% ($p < 0.01$). The administration of 7 cmH_2O CPAP in the supine position (P2 to P3) increased the FRC by 15% ±16% ($p < 0.01$), almost to the level in the sitting position. There was no difference between the FRC in the sitting position to the FRC in the supine position with CPAP 7cmH_2O ($p = 0.08$). See figure 3 for the FRC results. The Ventilation distribution showed a preference for dorsal regions in all three body positions studied. There was a nonsignificiant trend in the ventilation distribution towards ventral lung regions when changing from sitting to supine without CPAP (increase of 12% ± 51%; $p = 0.052$). The administration of 7 cmH_2O CPAP in the supine position did not change the distribution of ventilation (increase of 1% ±13%; $p = 0.289$). See figure 4 for the EIT results. Figure 5 displays an exemplary course of the thoracic impedance in ventral and dorsal lung regions of one volunteer.

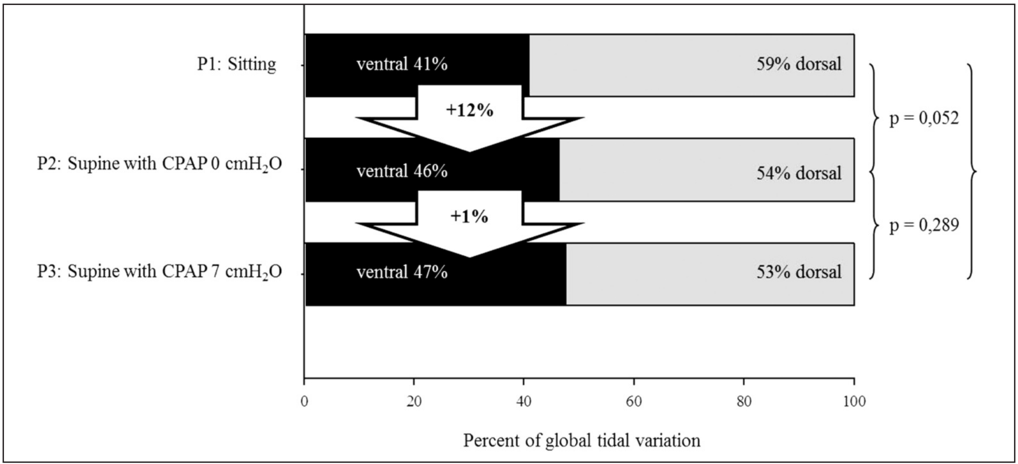

Figure 4: Ventilation distribution. Fraction of ventral and dorsal regions of global tidal variation. Values are means. (CPAP: continuous positive airway pressure, P1-3: body positions studied, see figure 1)

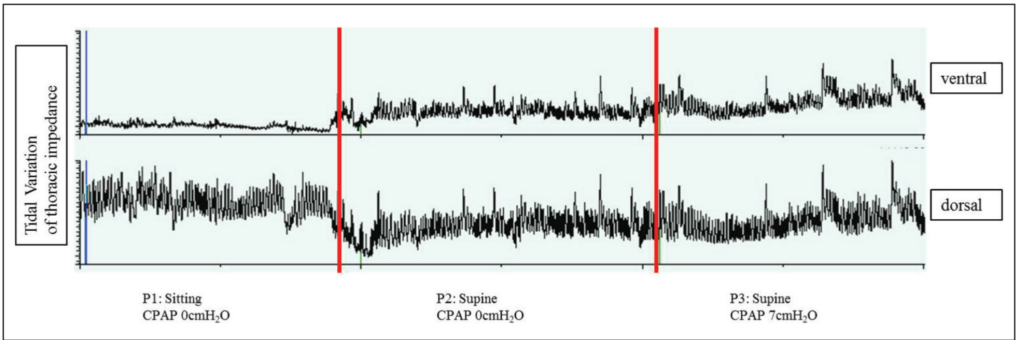

Figure 5: Course of the thoracic impedance in an example volunteer in the three body positions studied. Tidal Variation increased in the ventral parts of the lungs when changing from the sitting to the supine position. There was no visible change of ventilation distribution after administration of CPAP 7cmH_2O in the supine position. (CPAP: continuous positive airway pressure, P1-3: body positions studied, see figure 1)

Discussion

The main result of our study is that CPAP of 7cmH_2O was able to restore a reduced FRC in healthy volunteers, but did not change the ventilation distribution. The decrease in FRC of 16% by changing from the sitting to the supine position was lower than expected. According to the literature, a decrease of about 25% should occur. This goes back to a study published by Ibanez and colleagues, who determined the FRC of 50 male and 50 female volunteers in sitting and supine positions with the helium dilution method. Main differences between their and our group were age (33% vs 14% above the age of 40) and number of smokers (55% vs 18%). Both, age around 44 years [12] and smoking [13], will lead to a fall of the candidate´s closing volume below his FRC when lying supine. Is the FRC then measured with any kind of gas dilution or gas washout method (helium dilution by Ibanez et al, oxygen washin/washout in our study) in the supine position, this will lead to lower results for the FRC because lung areas behind closed airways will not be available for gas dilution or washin/washout. If the FRC is then compared in sitting and supine positions, a higher difference between the FRC sitting and supine will be measured in older subjects and smokers. However, FRC was measured to control for the expected loss of lung volume that is caused by going into a supine position. This could be found and meets our expectations. The increase of the FRC following the administration of CPAP 7 cmH_2O noninvasively in a supine position to the level of the FRC in the sitting position is in line with the findings of other studies [14, 15]. The shift of ventilation to ventral lung regions that was caused by going into a supine position is in accordance with physiological expectations. The dorsal parts of the lungs are still preferably ventilated. But in a supine position, since ventilation distribution follows gravity in healthy persons [16], the distance of the dependent and the independent parts of the lungs is smaller and therefore the difference in ventilation is smaller, too. Frerichs et al studied healthy, spontaneously breathing volunteers with EIT and found a similar ventilation distribution in the supine position [17]. In contrast to that, Andersson et al published data obtained in healthy volunteers, in which the ventral parts of the lungs were preferably ventilated in the supine position [18]. Here, again, we can see the influence of age on the patency of airways and lung volumes. While Andersson´s volunteers were 41 years old (+/- 8 years), the volunteers in Frerichs' study had a medium age of 24 (+/- 3 years), our volunteers of 31 years (+/-7). We did not observe ventilation redistribution after application of 7 cmH_2O and see two reasons for this finding. The first reason is the lack of atelectasis in our young and healthy volunteers in the supine position. We know from studies with computed tomography that going into a supine position does not cause formation of atelectasis in young and healthy persons [19]. In our volunteers, CPAP did not open any airways so no redistribution took place. While CPAP does open closed airways when existing, it can also hyperinflate already aerated lung areas [19]. When we use CPAP in ventilatory therapy, we are in a balancing act between a beneficial opening and a harmful hyperinflation of airways. While we did not see a ventilation redistribution with CPAP 7cmH_2O, Riedel et al saw a redistribution towards ventral lung regions in healthy volunteers administering CPAP of 10cmH_2O via a mouthpiece [20]. This indicates that hyperinflation can occur when CPAP is administered noninvasively. Our choice to apply CPAP 7cmH_2O might have been too low to see a ventilation redistribution [21]. The limitation of this study regarding the clinical application of our results is that young, healthy volunteers were examined. Their physiologic responses to the interventions cannot be compared to those of elderly, respiratory distressed patients in an ICU or respiratory care unit. As we only studied the impact of CPAP on FRC and distribution of ventilation, no statement concerning the influence of assisted spontaneous breathing, e.g. pressure support ventilation, in patients can be made. Also, a distressed patient might not be able to comply with our study design. Patients tend to cough, move and try to speak and therefore disturb measurements. Still, our results show that not only in intubated but also in noninvasively ventilated persons ventilation distribution can be monitored with electrical impedance tomography. We conclude that a noninvasive CPAP of 7cmH_2O restores a reduced FRC in healthy subjects, but does not change ventilation distribution. In a following study with patients, we expect to see ventilation distribution changes which will allow to optimise noninvasive ventilation individually, guided by EIT. With EIT more widely used in the clinical setting, we expect it to become a valuable tool in the optimization of noninvasive ventilation.

Acknowledgements

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Conflicts of interest

The FRC device and the EIT device used in this study were provided by Draeger Medical, Luebeck, Germany, without charge. The author Hermann Heinze received honoraria from Draeger Medical, Luebeck, Germany. The author Torsten Meier received one honorarium from Draeger Medical, Luebeck, in 2011. The authors Jan Karsten and Angela Schindler have no conflicts of interest.

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