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# The value of electrical impedance tomography in assessing the effect of body position and positive airway pressures on regional lung ventilation in spontaneously breathing subjects

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**Abstract** *Objective:* Functional electrical impedance tomography (EIT) measures relative impedance changes in lung tissue during tidal breathing and creates images of local ventilation distribution. A novel approach to analyse the effect of body position and positive pressure ventilation on intrapulmonary tidal volume distribution was evaluated in healthy adult subjects. *Design and setting:* Prospective experimental study in healthy adult subjects in the intensive care unit at university hospital. *Subjects:* Ten healthy male adults. *Interventions:* Change in body position from supine to prone, left and right lateral during spontaneous breathing and positive pressure support ventilation. *Measurements and results:* EIT measurements and multiple-breath sulphur hexafluoride ($SF_6$) washout were performed. Profiles of average relative impedance change in regional lung areas were calculated. Relative impedance time course analysis and Lissajous figure loop analysis were used to calculate phase angles between dependent or independent lung and total lung ($\phi$). EIT data were compared to $SF_6$ data washout measuring the lung clearance index (LCI). Proposed EIT profiles allowed inter-individual comparison of EIT data and identified areas with reduced regional tidal volume using pressure support ventilation. Phase angle $\phi$ of dependent lung in supine position was 11.7±1.4°, in prone 5.3±0.5°, in right lateral 11.0±1.3° and in left lateral position 10.8±1.0°. LCI increased in supine position from 5.63±0.43 to 7.13±0.64 in prone position. Measured $\phi$ showed inverse relationship to LCI in the four different body positions. *Conclusions:* EIT profiles and $\phi$ of functional EIT are new methods to describe regional ventilation distribution with EIT allowing inter-individual comparison.

**Keywords** Body position · Electrical impedance tomography · Intrapulmonary tidal volume distribution · Multiple-breath nitrogen washout · Positive airway pressures · Regional lung ventilation

## Introduction

Optimal respiratory support in acute respiratory distress using either invasive or non-invasive mechanical ventilation aims to improve ventilation distribution and treat hypoxia. Use of high end-expiratory pressures with low tidal volume and change in body position from supine to prone in patients with acute lung injury (ALI) improves oxygenation [1] but may increase arterial $CO_2$ tension [2]. Body position dependent ventilation distribution has been investigated in the past by two fundamentally different techniques: inert gas mixing techniques such as multiple-breath nitrogen washout [3] and imaging techniques such as computer tomography (CT) [4]. Each of these techniques is associated with specific models and experiments and thus is intrinsically limited.

Electrical impedance tomography (EIT) has recently emerged as a new imaging technique for bedside monitoring of ventilation distribution. EIT can identify and image spatial impedance changes associated with local air filling and emptying of the lungs during spontaneous and mechanical ventilation [5]. EIT accurately measures changes in end-expiratory level and describes regional ventilation distribution by measurement of local impedance change [6]. Functional EIT images are obtained by off-line analysis of impedance changes and compared with baseline data of the same subject [7]. Frerichs et al. [4] showed that time course analysis of local impedance change in selected lung areas provides a good estimate of local tidal volume change. With positive pressure support during invasive or non-invasive ventilation inspiratory air is directed into lung areas with higher compliance, and these areas are at risk of hyperinflation and barotrauma. These lung compartments with different lung compliance have different time constant for emptying and filling. The time course analysis of functional EIT can detect asynchronous filling and emptying of lung compartments [8] but has not been evaluated using positive pressure support.

The aim of the study was to describe and evaluate a novel approach to measure ventilation distribution using functional EIT. We report in healthy adults the asynchronous filling and emptying of lung areas during spontaneous breathing in four different body positions and compare functional EIT results with those from the multiple breath sulphur hexafluoride washout (MBSF$_6$W) technique to quantify ventilation distribution. In the same spontaneous breathing subjects the effect of various pressure support levels on tidal volume distribution within the lung was further investigated.

## Materials and methods

### Study design

MBSF$_6$W and EIT measurements were performed in ten healthy volunteers 26–51 years of age. We included only male subjects to exclude any effect of sex on EIT results [9]. Subjects were placed in supine, prone, left lateral and right lateral positions. All subjects were breathing through a mouth piece and an ultrasonic flow metre to measure flow and volume during tidal breathing. Subjects were instructed to breathe with a tidal volume of 1 l using a visual feedback on a computer screen. Measurements were made using MBSF$_6$W and EIT simultaneously during tidal breathing at 0 cmH$_2$O continuous airway pressure (CPAP) in supine, prone, right and left lateral positions and whilst their breathing was supported by a ventilator (Siemens Servo 300, Siemens-Elma, Solna, Sweden). Subjects breathed at 5 and 10 cmH$_2$O CPAP as well as using 5 cmH$_2$O of pressure support at 0 and 5 cmH$_2$O positive end expiratory pressure (PEEP). Measurements were made in triplicate at all levels of respiratory support. The study had been approved by the local ethic committee (Human Research Ethics Committee of Mater Health Services).

### MBSF$_6$W

The MBSF$_6$W method has been previously described in detail in spontaneously breathing infants and ventilated children [10, 11]. An adult sized ultrasonic flow metre (Spiroson, Ecomedics, Dürnten, Switzerland) with sealed side chambers was used for our measurements [11]. Subjects inhaled from a reservoir bag containing a gas mixture of 5% SF$_6$, 21% oxygen and 74% nitrogen through a two-way valve system. Once the lungs were equilibrated with the SF$_6$ mixture, the subject was disconnected from the reservoir bag during expiration and inhaled room air. Exhaled SF$_6$ volume was measured until end-expiratory SF$_6$ reached 0.1% of the concentration prior to washout. Functional residual capacity (FRC) was calculated by dividing initial SF$_6$ concentration by exhaled SF$_6$ volume. Lung clearance index (LCI) was calculated using the cumulative exhaled volume (until end-expiratory SF$_6$ concentration reached 1/40 of initial SF$_6$ concentration) divided by FRC [12]. The 1st to 0th moment ratio ($M_1/M_0$) was calculated using MBSF$_6$W [12]. Physiological dead space ($V_D$) was calculated using the Fowler method.

### EIT

EIT is a relatively new technique generating cross-sectional images of the studied subject based on the measurement of surface electrical potentials resulting from an excitation with known small electrical currents (5 mamp and 50 kHz). Both the voltage measurements and current injections take place between pairs of electrodes of a 16-electrode array attached on the chest circumference below the nipple line. EIT images are generated from the collected potential differences and the known excitation currents using weighted back-projection in a 32×32 pixel matrix [13]. Each pixel of the scan shows the instantaneous local relative impedance change with respect to a reference state of local impedance. A Goettingen GoeMF 1 EIT tomograph (Sensormedics/VIASYS healthcare, The Netherlands) was used in the current study with a frame rate of 13 Hz [14]. For data acquisition and reconstruction of functional EIT images software provided with the equipment was used [15]. Functional EIT data were further analysed off-line using Math_Lab 6.5.1 (MathWorks) and Labview software 6.1 (National Instruments).

### Methods of EIT analysis

The reference state used for EIT was regular tidal breathing of 1 l per breath in supine position. EIT was measured during 1 min periods. EIT data were further analysed by calculating the mean relative impedance change in any pixel for the 1-min measurement period. Based on the 32×32 pixel matrix the mean relative impedance change of 32 rows starting from the independent to the dependent lung was calculated and a profile of relative impedance change generated [16]. Profiles for all ten subjects were created. Time course of relative impedance change during the EIT measurement was calculated for the global lung and for four regions of interest (ROI); the left, right, anterior and posterior lung. Cardiac oscillations of the EIT signal were filtered with low pass filter at 0.5 Hz. Impedance change in each ROI was plotted against global lung impedance change in an XY graph. The upper panel of Fig. 1 shows the time course of a measurement obtained in left lateral position and the lower panel the corresponding loop plot. The phase angle $\phi$ was determined by measuring the ratio of the width of the loops thus formed at the point when global relative impedance change shows a zero crossing from inspiration to expiration and overall excursion of local relative impedance change and then taking the arcsin of this number: $\phi$= arcsin (A/B), where A and B are the amplitudes of the dependent or independent lung when global lung impedance is zero and maximal, respectively (Fig. 1). A similar method has been used to describe asynchrony of abdominal

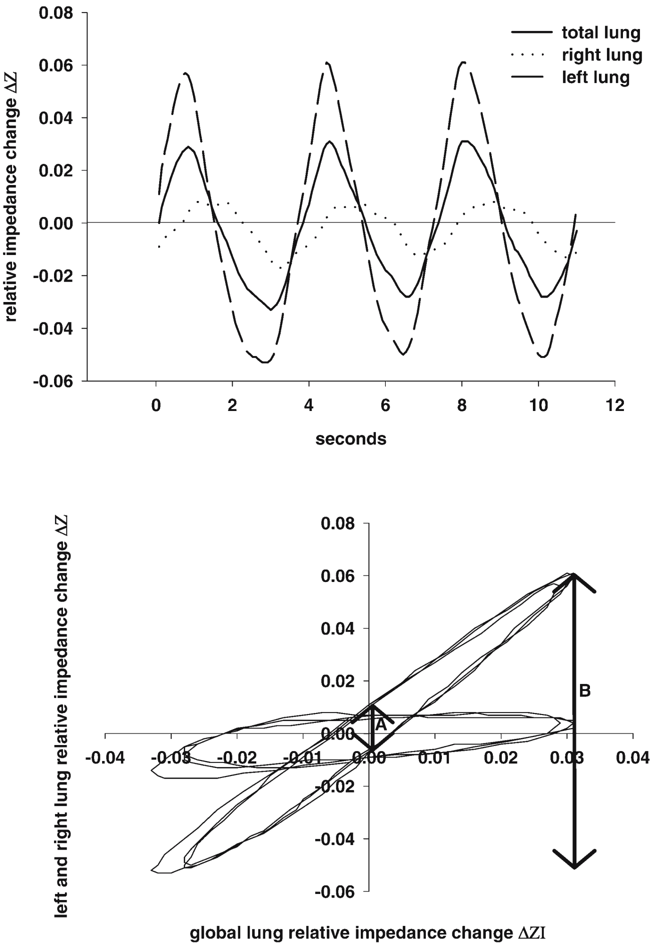

**Fig. 1** *Upper panel* Time course of relative impedance change (ΔZ) of a healthy adult in left lateral position; *continuous line* relative impedance change measured for the total lung; *bold interrupted line* that measured in the left lung; *dotted line* that measured in the right lung. *Lower panel* Loop plot of the right and the left lung vs. the total lung; *A*, *B* the parameters used to calculate the phase angle (see text)

to chest wall excursion [17]. The loops have a direction of rotation, which is expressed by positive $\phi$ (clockwise) or negative $\phi$ (anticlockwise). As a measure of asynchronous emptying the difference of the phase angle ($\Delta\phi$) of the dependent and independent lung was calculated. Mean relative impedance change between end-inspiration and end-expiration during the 1-min measurement period was calculated and the percentage of local (ROI) relative impedance change was obtained.

### Statistics

Data are presented as means and standard errors. Parameters of MBSF$_6$W and EIT were compared to baseline data in supine position using the paired *t* test. Differences as the level of $p<0.05$ were considered significant.

## Results

FRC and V$_D$ were significantly in prone position than in supine using zero CPAP (Table 1). LCI was higher in prone, right and left lateral positions than in supine, but only the change in prone position reached statistical significance. M$_1$/M$_0$ remained unchanged in all four positions using zero CPAP.

Table 2 displays percentage of ventilation of left and right lung in the four body positions measured by EIT using zero CPAP. The dependent lung in lateral decubitus position receives significantly more ventilation than the independent lung. Figure 2 displays the EIT profiles of all ten subjects breathing at 0 CPAP, 10 CPAP (left panel), and 0 PEEP and 5 PEEP with 5 cmH$_2$O pressure support (right panel) in supine, prone, right and left lateral positions. In lateral decubitus position the independent lung showed reduced local ventilation with 10 CPAP. This effect was caused by decreased total relative impedance change from 0 to 10 CPAP, as the area under the curve of the profiles remained unchanged for each body position (26.8±2.5 at 0 CPAP and 28.9±3.6 at 10 CPAP in supine, 25.6±2.7 at 0 CPAP and 25.7±1.9 at 10 CPAP in prone, 23.7±2.7 at 0 CPAP and 22.7±1.5 at 10 CPAP in right lateral, and 23.7±2.7 at 0 CPAP and 22.9±2.5 at 10 CPAP in left lateral position). In supine position ventilation in the posterior (dependent) lung remained unchanged from 0 to 10 CPAP but increased in the anterior (independent) lung. In prone position, however, the dependent (anterior)

**Table 2** Proportion of ventilation distribution into right and left lung in four different body positions on zero CPAP in ten healthy subjects

| Position | Left lung (%) | Right lung (%) |
|---|---|---|
| Supine | 49±1 | 51±1 |
| Prone | 51±1 | 49±1 |
| Right lateral | 35±3* | 65±3* |
| Left lateral | 56±4* | 44±4* |

* $p\leq0.05$ vs. supine position

**Table 1** Results of sulphur-hexafluoride washout in ten health subjects performed in four different body positions on zero CPAP (*FRC* functional residual capacity, $V_T$ tidal volume, *LCI* lung clearance index, $M_1/M_0$ first to zeroth moment, $V_D$ dead space)

| Position | FRC (ml) | V$_T$/FRC | LCI | M$_1$/M$_0$ | V$_D$ (ml) |
|---|---|---|---|---|---|
| Supine | 2776±193 | 0.36±0.03 | 5.63±0.43 | 1.91±0.51 | 119±12 |
| Prone | 3079±225* | 0.32±0.03 | 7.13±0.64* | 2.00±0.19 | 138±17* |
| Left lateral | 3077±342 | 0.32±0.03 | 6.27±0.44 | 1.86±0.16 | 126±7 |
| Right lateral | 2923±273 | 0.34±0.03 | 6.65±0.52 | 1.89±0.15 | 117±7 |

* $p\leq0.05$ vs. supine position

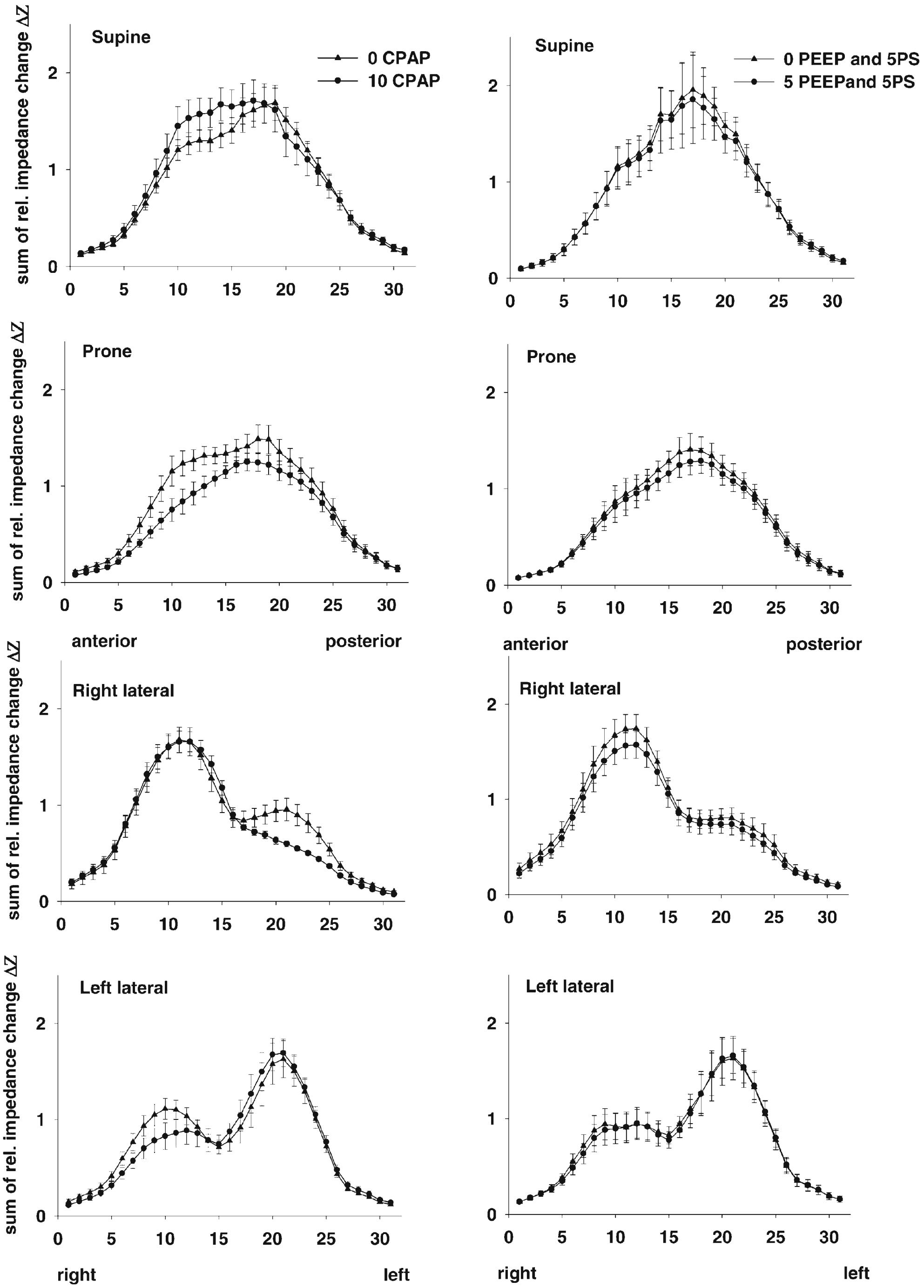

**Fig. 2** Profiles of all ten subjects in supine, prone, right and left lateral positions. Profiles were generated using 32 segments starting from the independent to the dependent lung and plot the sum of relative impedance change measured in each segment. *Left* Profiles are displayed when subjects were breathing with 0 or 10 CPAP; *right* profiles when subjects were breathing with pressure support of 5 cmH$_2$O at 0 and 5 cmH$_2$O PEEP

lung showed reduced ventilation at 10 CPAP. Profiles at 5 CPAP in the four positions are not displayed as they did not differ from those at 0 CPAP.

Table 3 presents all measured phase angles during tidal breathing at different CPAP levels and pressure support. The dependent lung showed a positive phase angle in all four body positions. Figure 3 plots $\Delta\phi$ and LCI for supine, prone, right and lateral positions.

## Discussion

Functional EIT is a relatively new technique to measure local ventilation distribution. The findings of this study demonstrate that functional EIT can measure gravity-dependent asynchronous emptying of the lung in different body positions and characterises local tidal volume distribution at different levels of pressure support. Although

**Table 3** Phase angles dependent and independent lung in four different body positions in ten healthy subjects ($\phi$ phase angle, *CPAP* continuous positive airway pressure, *PEEP* positive end expiratory pressure, *PS* positive pressure support)

| Pressure ($cmH_2O$) | $\phi$ Dependent lung (°) | $\phi$ Independent lung (°) | *p* |
|---|---|---|---|
| Supine | | | |
| 0 CPAP | 11.7±1.4 | −5.0±1.5 | <0.001 |
| 5 CPAP | 15.1±2.0 | −9.3±1.7 | <0.001 |
| 10 CPAP | 14.5±1.9 | −15.4±3.3 | <0.001 |
| 5 PS | 10.9±0.8 | −3.4±1.3 | <0.001 |
| 5 PEEP+5 PS | 14.0±1.9 | −5.5±1.9 | <0.001 |
| Prone | | | |
| 0 CPAP | 5.3±0.5 | 3.1±0.8 | 0.049 |
| 5 CPAP | 6.6±0.6 | 1.8±1.4 | 0.032 |
| 10 CPAP | 6.6±0.6 | 0.1±1.3 | 0.008 |
| 5 PS | 5.8±0.4 | 3.1±0.5 | 0.006 |
| 5 PEEP+5 PS | 6.6±0.5 | 2.0±0.7 | 0.003 |
| Right lateral | | | |
| 0 CPAP | 11.0±1.3 | −14.3±2.9 | <0.001 |
| 5 CPAP | 12.2±1.4 | −17.6±3.7 | <0.001 |
| 10 CPAP | 11.2±1.3 | −19.6±3.4 | <0.001 |
| 5 PS | 9.9±1.2 | −13.6±3.0 | <0.001 |
| 5 PEEP+5 PS | 10.1±1.2 | −10.6±3.5 | <0.001 |
| Left lateral | | | |
| 0 CPAP | 10.8±1.0 | −10.8±1.6 | <0.001 |
| 5 CPAP | 9.3±1.1 | −11.5±3.0 | <0.001 |
| 10 CPAP | 9.7±1.3 | −15.8±5.7 | <0.001 |
| 5 PS | 8.2±1.1 | −8.9±2.7 | <0.001 |
| 5 PEEP+5 PS | 6.9±1.1 | −6.8±4.9 | <0.001 |

our data are limited to healthy subjects, and rather large lung areas were analysed, the proposed method may be powerful enough to analyse uneven ventilation in sick lungs and more specific lung regions. EIT data commonly is presented using a pixel matrix with a colour or grey scale to quantify regional impedance changes. These EIT images are difficult to compare among individuals. EIT profiles and phase angles as presented in this study allow convenient inter-individual comparison.

## EIT profiles

Frerichs et al. [4] have previously confirmed that EIT more accurately measures regional volume change than electron-beam CT in mechanically ventilated pigs. They further reported that delivered tidal volume in supine position is mostly directed into the dorsal (dependent) lung region. Hinz et al. [16] demonstrated in an acute lung injury animal model using different modes of ventilatory support that regional ventilation is well correlated with the results of single photon emission CT. We measured regional ventilation distribution with a similar EIT data acquisition technique as in the above studies. We standardised the breathing pattern of 1 l per breath was used for two reasons: first, we had to eliminate the intrinsically failure of EIT for inter-individual comparison, and, second, it has been demonstrated that ventilation distribution is critically dependent on size of tidal volume [18].

The aim of this study was to investigate whether tidal volume distribution is dependent on body position, and whether the use of CPAP or pressure support ventilation affects tidal volume distribution. We found that in healthy adult subjects the dependent lung is better ventilated irrespective of body position and pressure support (Table 2). In lateral body position and with 10 CPAP less tidal volume was directed into the independent lung, possibly due to a shift on the pressure volume curve to the right flatter part of the sigmoid curve with a reduced local tidal volume. In supine position, however, the independent lung benefits from 10 CPAP, possibly due to reduced dorsal displacement of the mediastinum and hence less-gravity dependent strain and better ventilation distribution of the anterior lung. Pressure support with or without PEEP did not affect tidal volume distribution as observed with 10 CPAP alone. The higher the CPAP level the more the diaphragm is displaced caudally and the whole lung experiences a shift in the cranio-caudal axis. Therefore it is possible that different anterior lung areas are measured with 10 CPAP than with 0 CPAP.

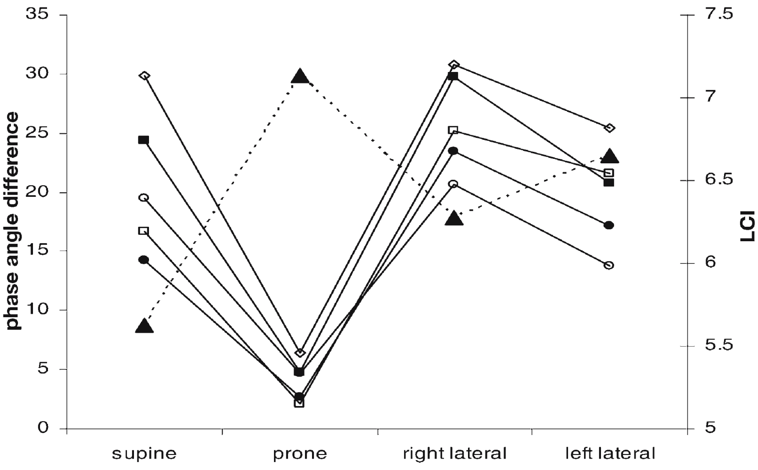

**Fig. 3** Change in lung clearance index in the different positions and change in phase angle $\phi$ differences in supine, prone, right and left lateral positions. *Open squares* 0 CPAP; *filled squares* 5 CPAP; *open diamonds* 10 CPAP; *filled circles* 5 $cmH_2O$ PS; *open circles* 5 PEEP+5 $cmH_2O$ PS; *filled triangles* LCI)

Several factors influence spatial and anatomical ventilation distribution in healthy lungs and the concept of asynchronous filling or emptying of the lung is not new. Using inspiratory flow rate of less than 1.5 l/s the dependent lung is preferentially ventilated [19]. Bennet et al. [20] have recently shown that the left lung is preferentially ventilated during slow inspiration between 50% and 100% total lung capacity. Rehder et al. [21] described in anaesthetised, spontaneously breathing and in anaesthetised ventilated men that the independent lung receives more ventilation. On the other hand, Frerichs et al. showed in non-anaesthetised healthy subjects using quantitative analysis of the change in EIT that the dependent lung is better ventilated. Our data support those of Frerich et al. [4] but contradicts those of Rehder et al. [21] as our data show that CPAP and pressure support does not affect spatial ventilation distribution. However, the measurement conditions used by Rehder et al. were significantly different.

The proposed method using EIT profiles may be a useful approach to compare inter-individual regional ventilation distribution in mechanically ventilated patients. EIT profiles may eventually discriminate between responders and non-responders in clinical trials investigating the effect of body position or change in CPAP on outcome. As shown in Fig. 2, the effect of increased CPAP causing reduced local ventilation can be described by this technique.

## EIT phase angle analysis

Ventilation maldistribution is caused by diffusion dependent and diffusion-convection dependent ventilation inhomogeneity [19] and can be quantified using inert gas washout techniques. This allows the measurement of gravity dependent ventilation distribution with high accuracy, but lung areas with impaired ventilation distribution cannot be located as with CT. CT of the lung exhibits highly accurate information on pathological tissue alterations, whereas current EIT technology does not have this high degree of resolution. The time course analysis of local relative impedance change during tidal breathing allows dynamic interpretation of ventilation distribution. In principle functional EIT measures local relative impedance changes which correspond to local tidal volumes [4]. Hence a tidal wave form of relative impedance change in a ROI can be obtained (Fig. 1, upper panel). If such an ROI has a different time constant (i.e. a longer time constant of the right lung) than the total lung, the relative impedance change in the right lung shows a shift in phase compared to relative impedance change in the total lung. To express the magnitude of this shift in phase a phase angle can be calculated by using an XY plot of the two sinusoidal signals. The ratio of the width of the loop at zero crossing on the X-axis and the overall excursion of the loop is taken, and the arcsin of this ratio gives the phase angle.

We observed a remarkable asynchronous emptying of the dependent and independent lung in supine, prone, right and left lateral positions. For instance, the example in Fig. 1 shows that the right lung in left lateral position is still expiring while the left lung has already initiated inspiration. This phenomenon has been termed *Pendelluft* between the right and left lungs [22]. Anatomically the dependent and independent lung areas are less well separated in the anterior to posterior axis than in left to right (left and right main bronchus). Ventilation distribution measured with MBSF$_6$W in right or left lateral position is similar to that in supine position. But the phase angles differences are smaller, and LCI as an index of ventilation distribution is higher in prone position. Direct comparison of EIT and MBSF$_6$W requires caution as EIT measurements assess ventilation distribution of a single cross-sectional slice of the lung only. Hahn et al. [8] used a similar technique to measure asynchronous emptying of the lungs. They used an EIT system with lower sampling frequency and did not investigate all body positions or the effect of pressure support.

Why is ventilation distribution less even in prone position? FRC and $V_D$ were increased in prone position, which may have caused increased ventilation maldistribution. Previous studies by Rodriguez et al. [23] showed that ventilation distribution remained unchanged when measured in supine and prone positions using multiple breath inert gas washout. These authors, however, used a specially built stretcher to avoid abdominal compression and cranial displacement of the diaphragm. They further analysed only measurements with similar FRC in supine and prone positions. This physiological approach is certainly correct if only gravity-dependent effects on ventilation distribution are investigated. However, our study design aimed to investigate ventilation distribution in positions commonly used in intensive care settings. The impaired ventilation distribution in prone position may further be explained by a decreased ratio of tidal volume to FRC in prone position. Groenkvist et al. [24] reported similar results in healthy adult. These authors investigated ventilation distribution in standing and supine position using three different sizes of tidal volumes. They found showed that ventilation distribution improves with larger tidal volume to FRC ratio in standing or supine position.

What are the implications and limitations of these results for the use of EIT in patients requiring mechanical ventilation? Interpretation of our finding cannot be translated for paralysed patients needing mechanical ventilation. However, spontaneous breathing with pressure support is currently the most common form of mechanical ventilation in patients with lung disease. When asynchronous emptying of the dependent and independent lungs in disease is observed, one must consider body position as a strong determining factor. The anatomical position of the EIT electrodes is important as any cranial or caudal placement of the electrodes may interfere significantly with results. We further need to determine in subjects with lung disease whether similar findings may be found. EIT profiles and EIT time course analysis may be useful in larger clinical trials to separate responders from non-responders when effect of position change and CPAP/PEEP is investigated. Mean impedance changes as used in the present study cannot differentiate between changes in volume of air- or fluid-filled spaces within the lungs. Changes in mean impedance offer the possibility to follow shifts in regional lung volume and/or fluid content, for example, monitoring of the development of hyperinflation. Absolute values of specific tissue impedance are available using adequate image reconstruction algorithms. This approach may in principle offer a direct access to discriminate air or fluid compartments in the thorax by EIT.

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