Sabine Krueger-Ziolek*, Bo Gong, Bernhard Laufer and Knut Moeller

Impact of lung volume changes on perfusion estimates derived by Electrical Impedance Tomography

Abstract: Electrical Impedance Tomography (EIT), an imaging technique which operates non-invasively and without radiation exposure, provides information about ventilation- and cardiac-synchronous (pulsatile) changes in the lung. It is well known, that perfusion within the thorax is influenced by lung volume or intrathoracic pressure. In this observational study, it shall be investigated if this phenomenon can be monitored by EIT. Therefore, the impact of the amount of air within the lung on the pulsatile EIT signal was evaluated by carrying out EIT measurements with a spontaneously breathing lung healthy subject holding the breath at three different inspiratory and three various expiratory volume levels during normal tidal breathing. For EIT data analysis, a region of interest was defined by including lung tissue and excluding the heart region. The EIT data revealed, that the shape and the amplitude of the pulsatile EIT signal (evaluated per heartbeat) during the phases of breath holding were dependent on the enclosed lung volume. For lung volumes > 4 L, the amplitude of the pulsatile EIT signal increased with rising inspiratory level and the shape remained almost unchanged. For lung volumes < 4 L, a change in shape was visible but the amplitude remained more or less the same with decreasing expiratory level. Since the results of this observational study show that the pulsatile EIT signal is influenced by the lung volume, it might be used in future to draw conclusions of cardiac-pulmonary interactions or intrathoracic pressure states, benefitting the treatment of intensive care patients.

Keywords: Electrical Impedance Tomography, perfusion, ventilation, pulmonary pressure, spontaneous breathing

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***Corresponding author: Sabine Krueger-Ziolek:** Institute of Technical Medicine, Furtwangen University, Jakob-Kienzle-Straße 17, Villingen-Schwenningen, Germany, krue@hs-furtwangen.de
Bo Gong, Bernhard Laufer, Knut Moeller: Institute of Technical Medicine, Furtwangen University, Villingen-Schwenningen, Germany

1 Introduction

Due to the continuously rising number of patients with pulmonary diseases, the demand of new technologies for lung function monitoring increased.

Non-invasiveness, no radiation and a high temporal resolution are just a few advantages characterizing Electrical Impedance Tomography (EIT), a still relatively new functional imaging modality. Changes in impedance of the lung tissue, induced by variations in air and blood volume during respiration, can be reconstructed on the basis of potentials measured at the surface of the thorax [1,2].

Depending on the applied EIT system, surface potentials are measured with 16 to 32 electrodes which are attached at the thorax in the same distance to each other in a transversal plane. For the measurements, the injection of a small alternating current (for example 5 mA, 50 kHz) is necessary, which is harmless for the patient. The reconstructed impedance images can be used by clinicians to assess changes in regional ventilation distribution within the lung.

So far, EIT is mainly employed for ventilation distribution monitoring in mechanically ventilated patients at the intensive care unit (ventilation therapy) [3,4], or for regional lung function monitoring in spontaneously breathing patients with obstructive lung diseases (diagnosis, follow-up and therapy response) [5-7].

Besides ventilation monitoring, EIT can be utilized to determine cardiac-synchronous (pulsatile) relative impedance changes within the thorax. Impedance changes within the lung induced by blood volume changes can provide additional information on lung function (perfusion estimates), benefitting treatment and therapy. Although, several EIT studies dealing with lung perfusion have already been conducted, there are still many unanswered questions in this area of application. Most of the recent published studies were animal experiments or addressed the application during mechanical ventilation [8,9].

However, this observational study was carried out during spontaneous breathing to investigate the impact of lung

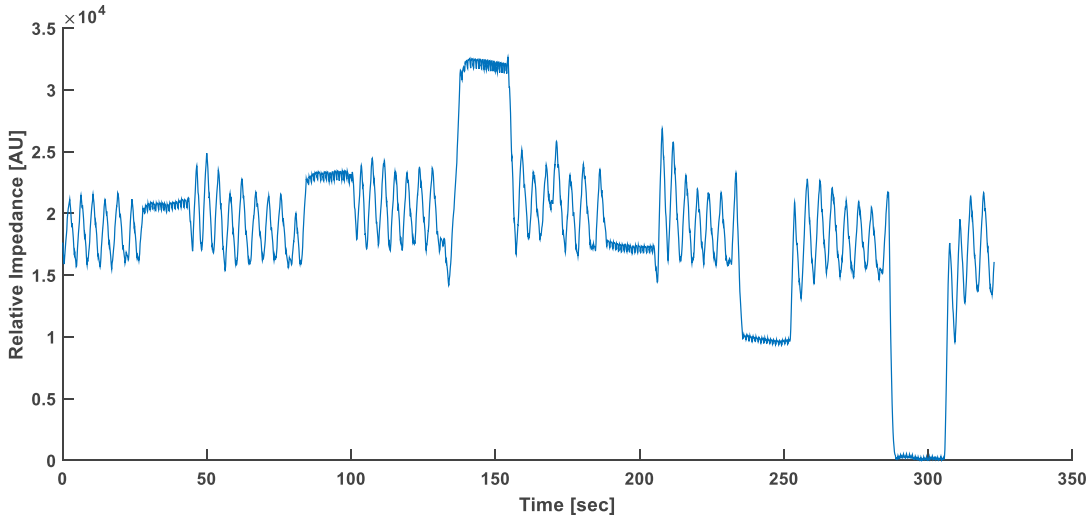

Figure 1: Relative impedance changes measured during normal tidal breathing as well as during breath holding phases at various inspiratory and expiratory volume levels.

volume on the pulsatile EIT signal. Since changes in lung volume induce changes in pulmonary pressure, and thus changes in perfusion, it was hypothesized that the pulsatile EIT signal may provide information on cardiac-pulmonary interactions, which may support the treatment of intensive care patients.

2 Methods

2.1 Study protocol

One lung healthy volunteer (male, 29 years, 184 cm, 77 kg) was performing normal tidal breathing in a body plethysmograph (PowerCube®Body+, Ganshorn Medizin Electronic, Germany) and after approx. 7 tidal breaths, the subject increased the inhaled breathing volume, held the breath at this inspiratory level for 10 to 12 seconds and returned to normal breathing afterwards. This scenario was done three times with various inspiratory volume levels. Subsequently, this procedure was carried out with three different expiratory levels.

In parallel, EIT data were collected at the 5th intercostal space (frame rate 50 Hz, 8 mA, 89 kHz) with a 16-electrode-system (PulmoVista®500, Dräger, Germany) (Figure 1).

For the sake of reproducibility, this measurement was executed two times as well as in reverse order, starting with various expiratory volume levels followed by different inspiratory volume levels.

2.2 EIT data processing

A FEM based linearized Newton-Raphson algorithm was applied to reconstruct EIT images with a resolution of 32 × 32 pixels (EIT Analysis Tool 6.1, Dräger, Germany), representing intrathoracic impedance changes. The following steps of the EIT data processing were implemented in MATLAB (R2017a, The Mathworks® Inc., Natick, USA). Since the body plethysmographic flow was measured with a sample rate of 200 Hz, the EIT data were interpolated to the same sample rate for further analysis.

To confine the evaluation of the pulsatile impedance changes to the lung, a region of interest was defined by including lung tissue and excluding the heart region. Therefore, one EIT image at the highest inspiratory volume level (shortly before breath holding started) was selected and the maximum value of this image was determined. 20% of this maximum value was set as a threshold, meaning that all pixel values of the selected image smaller than this threshold were not included to the lung region. The resulting lung contour was applied for all EIT images.

The heart region estimation was performed in the phase of breath holding at the lowest expiratory level. Since there is a phase shift between impedance changes of the lung tissue and the heart region during one heartbeat (based on changes in blood volume), it was possible to distinguish between lung tissue and the heart region. Pixels belonging to the heart region were specified during diastole to capture changes in heart position and size. The final ROI, which was applied to all EIT images, was defined by subtracting the heart region from the lung contour.

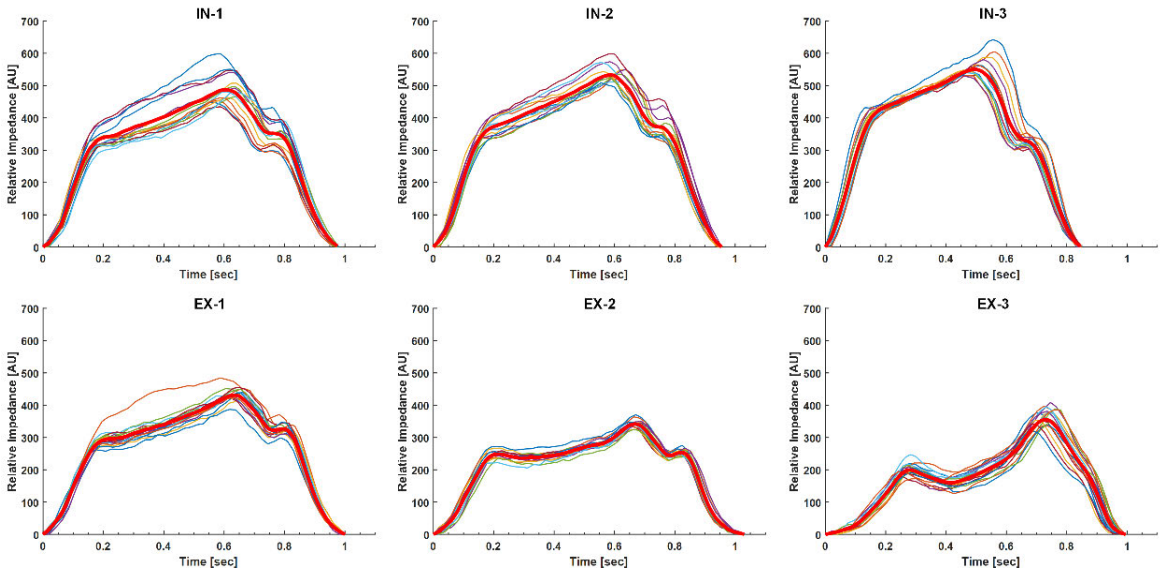

Figure 2: Pulsatile EIT signal sections (thin, colored lines) determined during the phase of breath holding at three different inspiratory volume levels (IN-1: *5.03 L*, IN-2: *5.55 L* and IN-3: *6.66 L*) and three various expiratory volume levels (EX-1: *4.35 L*, EX-2: *3.82 L* and EX-3: *2.68 L*) as well as the calculated mean signal (bold, red lines).

2.3 Data analysis

The pulsatile EIT signal measured during the phase of breath holding was subdivided in signal sections corresponding to the period of one heartbeat. A linear trend, obtained by the linear fit based on the start point and end point of each signal section, was removed from all signal sections respectively.

Since the length of time of the signal sections slightly varied, the time span of each signal section has been rescaled to the mean time span of all signal sections. Afterwards, the mean signal of all sections was calculated (Figure 2). This procedure was applied for all the six phases of breath holding (three inspiratory levels and three expiratory levels).

3 Results

Figure 2 exemplarily shows the individual pulsatile signal sections as well as the mean signal of all sections of the three various inspiratory levels (IN-1, IN-2 and IN-3) and of the three different expiratory levels (EX-1, EX-2 and EX-3) of one of the conducted measurements.

Using the body plethysmograph, it was possible to assess the lung volume at the time of breath holding. The following lung volumes were determined at the various inspiratory and expiratory volume levels: IN-1: *5.03 L*, IN-2: *5.55 L*, IN-3: *6.66 L*, EX-1: *4.35 L*, EX-2: *3.82 L* and EX-3: *2.68 L*.

According to Figure 2, the shape of the mean signal remains almost the same for lung volumes > 4 L. In this case, an increase in amplitude with rising lung volume is visible (EX-1: *430*, IN-1: *487*, IN-2: *533* and IN-3: *550*). A distinct change in the shape of the mean signal can be seen for smaller lung volumes (< 4 L). Here, the amplitude remains almost the same with decreasing expiratory level (EX-2: *341* and EX-3: *355*), although the area under the curve decreases (EX-2: *211*, EX-3: *168*). These observations (changes in shape and amplitude of the mean signal) could be made for all conducted measurements.

4 Discussion

The results of this observational study show that the enclosed air volume within the lung at breath holding influenced the measured pulsatile EIT signal in shape and amplitude. So far, the results are not clearly interpretable. EIT reveals a relation between lung volume and perfusion related signals. In principle, it is assumed that the pulsatile signals show a larger amplitude with decreasing pressure and vice versa. During inspiration, a larger blood volume is reaching the heart (increase in preload) which might lead to the increase in amplitude (IN-1, IN-2 and IN-3). In expiration, the opposite happens which in turn may lead to the smaller amplitudes as well as areas under the curve of the pulsatile signals (EX-1, EX-2 and EX-3). Other effects may be possible but further speculations e.g. about muscle activities, elastic recoil or cardiogenic oscillations during breath holding need to be investigated in further experiments.

However, results of this preliminary study demonstrate that the pulsatile EIT signal measured during breath holding is systematically affected by the size of lung volume implying cardiac-pulmonary interactions. Multiple measurements and changing breathing order confirmed intra-subject reproducibility of the results. Nonetheless, additional measurements with a higher number of subjects have to be undertaken to evaluate the inter-subject reproducibility of the results.

5 Conclusion

This observational study shows that the shape and the amplitude of the pulsatile EIT signal obtained during breath holding depend on the amount of air within the lung. It is suspected that changes in the pulsatile signal were mainly based on variations in pulmonary pressure inducing blood volume changes. Thus, EIT might be utilized in the future to non-invasively gain information about cardiac-pulmonary interactions, benefitting clinical sectors like intensive care.

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Author Statement

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