Selection of the Baseline Frame for Evaluation of Electrical Impedance Tomography of the Lungs

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***Abstract*—Electrical impedance tomography (EIT) is a promising modality for lung ventilation monitoring. It can provide information about the distribution of regional ventilation in predefined regions of interest (ROIs), as well as estimate several ventilatory parameters including tidal volume (V_T) or end-expiratory lung volume (EELV). The approaches for calculation of V_T and EELV are based on the values of global tidal variation (TV) and end-expiratory lung impedance (EELI) obtained by the means of functional EIT (fEIT). For reconstruction of fEIT data, a set of reference measurements, often called as a baseline frame, needs to be determined. The aim of the study is to show how setting of this baseline frame can influence the values of ROI, global TV and EELI and thus affect the estimation of V_T and EELV and the evaluation of lung recruitment as such. In order to study the effect of the baseline frame selection, an animal study (pigs, n=3) was conducted. The animals were anaesthetized and mechanically ventilated. Four incremental steps in positive end-expiratory pressure (PEEP), each having a value of 0.5 kPa were performed to reach a total PEEP level of 2.5 kPa. Continuous EIT monitoring was done during this PEEP trial. The obtained data were reconstructed using baseline frames chosen manually at five different PEEP levels. The selection of the baseline frames resulted in different values of global TV and EELI. Thus, when estimating V_T and EELV by means of fEIT, it is necessary to choose one common baseline frame for data reconstruction. However, the effect on the percentage values that express the distribution of regional ventilation is negligible and below clinical significance.**

Keywords—electrical impedance tomography; EIT; functional EIT; fEIT; region of interest; ROI; end-expiratory lung impedance; EELI; end-expiratory lung volume; EELV; positive end-expiratory pressure; PEEP; mechanical ventilation; monitoring; respiratory care Introduction

In clinical routine, computed tomography (CT) is considered as the gold standard for evaluation of lung recruitment and lung aeration inhomogeneity. Nevertheless, CT has disadvantages that should be taken into account, including a high dose of ionizing radiation, inaccessibility of CT bedside and impossibility of its continuous usage. Electrical impedance tomography (EIT) does not have these disadvantages; therefore, EIT might be a suitable alternative to CT for the lung monitoring. However, due to the physical principle used, the reconstruction problem of EIT is rather difficult and when compared with CT, the resulting images have a low spatial resolution [1, 2].

Currently, there are two principal types of EIT images: absolute and functional (often also called as "relative") [3]. Absolute images provide an information about the distribution of complex electrical impedance within the selected cross-section of the chest [4]. Their main advantage is a possibility to evaluate a development of lung tissue or a pulmonary disease and are thus greatly valuable, especially in neonatal intensive care [5, 6]. Unfortunately, to calculate absolute EIT images, precise information about the chest geometry and about the positon of electrodes is necessary. Since obtaining these parameters can be troublesome in clinical environment, a concept of functional imaging was developed to circumvent this problem. [7, 8]. In functional EIT (fEIT), the measured data are normalized using a vector of reference measurements [7]. This vector is frequently determined by choosing a reference frame (sometimes called as "baseline frame") or by calculation of average values over a certain time period [3]. The approach of fEIT eliminates most of the artifacts caused by the chest geometry, but the information about the complex electrical impedance is lost [3]. However, the evaluation of lung ventilation remains feasible. As no further information about the patient's chest or about the position of electrodes is necessary, fEIT imaging is becoming popular in clinical routine.

The interpretation of information provided by EIT is still rather difficult, even for experienced users [2]. Therefore, several approaches were developed to evaluate lung ventilation. In spatial domain, one of the basic methods is to split the image into the regions of interest (ROIs) and calculate the proportions of ventilation in these regions [9, 10]. Several studies also proved that some useful ventilation parameters can be estimated from fEIT measurements. Linear relationship has been shown between tidal volume (V_T) and global tidal variation (TV) values derived from fEIT when previous calibration is performed [11]. Similarly, good or moderate agreement has been found between end-expiratory lung volume (EELV) and end-expiratory lung impedance (EELI) in [12] and [13], respectively.

As the reconstruction of fEIT images is dependent on the setting of baseline frame, we hypothesized that also parameters derived from fEIT might be influenced by the selection of the baseline frame as well.

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The aim of the study is to show how setting of reference measurement (baseline frame) can influence the values of ROI, global TV and EELI and thus affect the estimation of V_T and EELV and the evaluation of lung recruitment as such.

I. Methods

The study was approved by the local Ethics Committee and is in accordance with Act No. 246/1992 Coll., on the protection of animals against cruelty. The measurements were performed at the accredited animal laboratory of the First Faculty of Medicine, Charles University in Prague.

Three crossbred Landrace female pig (*Sus scrofa domestica*) with a body weight 48±2 kg were used in this study.

A. Anesthesia and preparation

The animals were premedicated with azaperone (2 mg/kg IM). Anesthesia was initiated with ketamine hydrochloride (20 mg/kg IM) and atropine sulphate (0.02 mg/kg IM), followed by boluses of morphine (0.1 mg/kg IV) and propofol (2 mg/kg IV). A cuffed endotracheal tube (I.D. 7.5 mm) was used for intubation. Anesthesia was maintained with propofol (8 to 10 mg/kg/h IV) in combination with morphine (0.1 mg/kg/h IV) and heparin (40 U/kg/h IV). To suppress spontaneous breathing, myorelaxant pipecuronium bromide (4 mg boluses every 45 min) was administered during mechanical lung ventilation. Initially, rapid infusion of 1 000 mL of saline was administered intravenously, followed by a continuous IV administration of 250 mL/h to reach and maintain central venous pressure of 6 to 7 mmHg. Mixed venous blood oxygen saturation (SvO_2), pulmonary artery pressure (PAP) and continuous cardiac output (CO) were measured by Vigilance (Edwards Lifesciences, Irvine, CA, USA) monitor.

B. Ventilation

Conventional ventilator Hamilton G5 (Hamilton Medical AG, Bonaduz, Switzerland) was used in the (S)CMV mode with the following setting: respiratory rate 18 bpm, FiO_2 21 %, I:E 1:2 with initial positive end-expiratory pressure (PEEP) of 0.5 kPa. The initial V_T was set to 8.5 mL/kg of the actual body weight and was titrated to reach normocapnia ($PaCO_2$ 40 ± 1 mmHg). During the study protocol four increasing PEEP steps of 5 cmH_2O were performed. Each PEEP level was maintained at least for 3 minutes.

C. EIT measurements

PulmoVista 500 (Dräger Medical, Lübeck, Germany) was used for the EIT measurements. The electrode belt (size S) was attached to the chest of the animal at the level of the 6^{th} intercostal space. The frequency of the applied current was set to 110 kHz with amplitude of 9 mA. Data were acquired continuously with a frame rate of 50 Hz during the whole PEEP trial.

D. Data Processing

The measured data were pre-processed using Dräger EIT Data Analysis Tool 6.1 (Dräger Medical, Lübeck, Germany). For each PEEP level, baseline frame was manually chosen among EELI frames and data were reconstructed using these baseline frames as a reference.

The processing of reconstructed data was performed in MATLAB 2014b (MathWorks, Natick, MA, USA). Impedance waveforms were calculated as a sum of pixel values in fEIT images. To obtain the same level of EELI values for the lowest PEEP level, the global minimum value of each impedance waveform was subtracted from all its points. EELI values were determined as local minima on the impedance waveform (more detailed explanation of this approach is given in [14]). Similarly, end-inspiratory lung impedance (EILI) values were determined as local maxima in the impedance waveform. Global TV was calculated for each breath as a difference between EILI and EELI. Four ROIs of equal size were chosen in the fEIT images (Fig 1). This setting is the same as the default definition of zonal ROIs in PulmoVista 500 EIT system. For each ROI, fractional impedance in percentage was calculated. To compare the changes in ROI values, boxplots were created in STATISTICA (StatSoft, Inc., Tulsa, OK, USA).

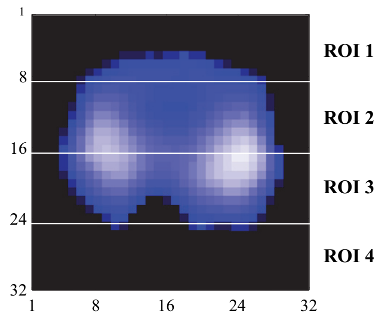

Fig. 1. Determination of the ROIs in the fEIT image.

II. Results

According to the study protocol, data from 3 animals were processed. The impedance waveforms were reconstructed using five manually selected baseline frames, each from different PEEP level. An example of the waveforms is presented in Fig. 2. Both the curves of EELI and EILI are dependent on the baseline frame selection. The differences increase with the incremental PEEP levels at which the baseline frame was chosen.

For each impedance waveform, the values of global TV, as well as the fractional impedance change in selected ROIs were calculated. The results presented in Fig. 2 show, that the values of global TV differ when baseline frames are selected from different PEEP levels. Comparison of ventilation distribution in ROIs for one of the animals is shown in Fig. 2 as well and the comparison of ROIs calculated at two selected PEEP levels using two different baseline frames is in Fig 3. The variation of ROI values computed from the data obtained using baseline frames selected at different PEEP levels is much smaller than the variation in data provided by the EIT system PulmoVista 500 during mechanical ventilation of the animal. When reconstructing a dataset consisting of several measurements

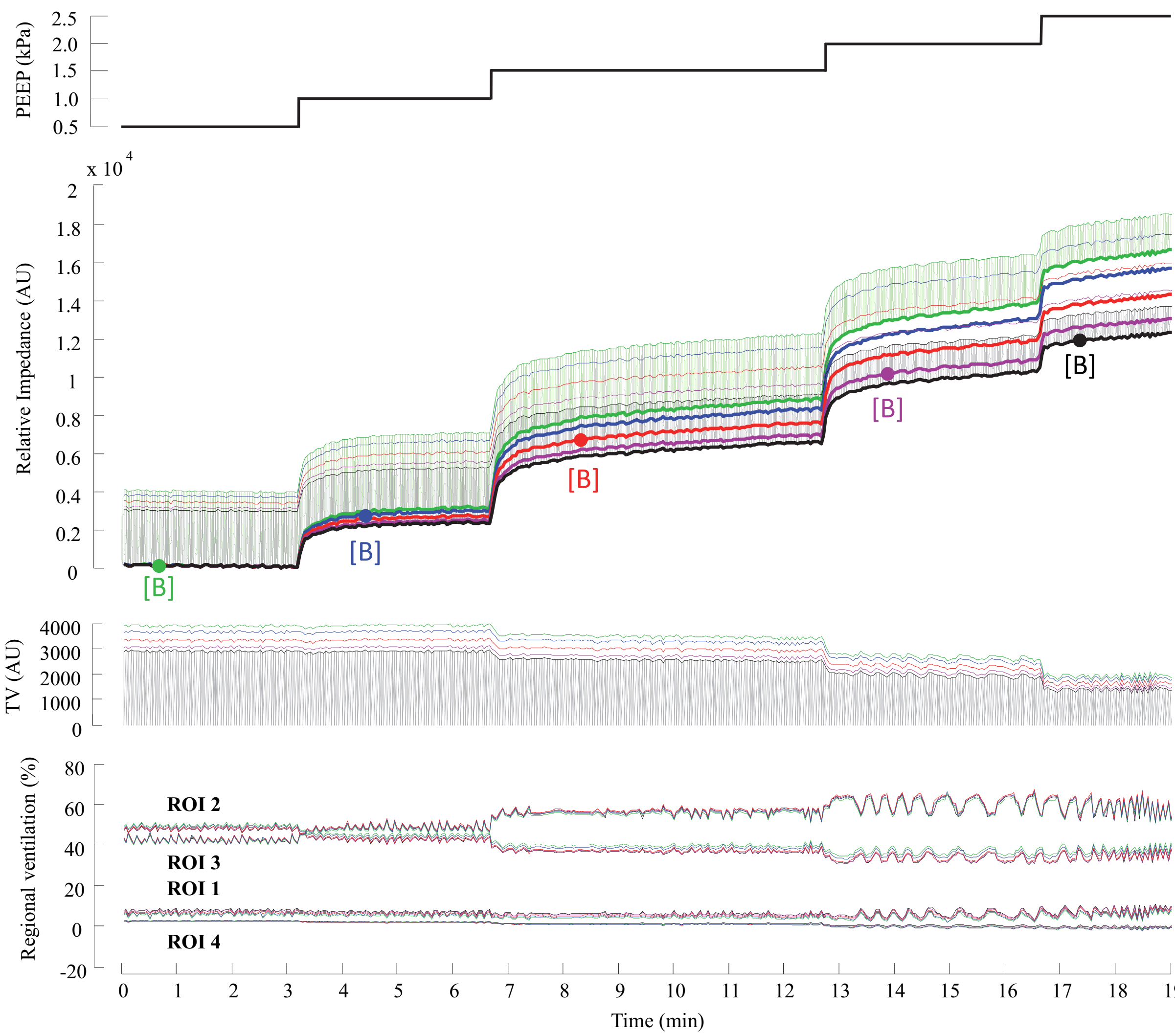

Fig. 2. Processing of impedance waveforms for evaluation of end-expiratory lung impedance (EELI), global tidal variation (TV) and fractional impedance in regions of interest (ROIs) during changes in positive end-expiratory pressure (PEEP). Top graph: PEEP values in time. The second graph from the top: impedance waveforms reconstructed for baseline frames selected for each PEEP level (marked as [B]; green: 0.5 kPa, blue: 1.0 kPa, red: 1.5 kPa, magenta: 2.0 kPa and black: 2.5 kPa). The bold line connects the end-expiratory lung impedance (EELI) points, the thin line connects the end-inspiratory impedance points. Only two complete impedance waveforms (light green for the baseline frame chosen at PEEP level of 0.5 kPa and gray for the baseline frame chosen at PEEP level of 2.5 kPa) are presented for clarity. The second graph from the bottom: comparison of global TV calculated from impedance waveforms that were reconstructed using the selected baseline frames. The complete data for baseline frame chosen at PEEP 2.5 kPa (gray) are presented for clarity. Bottom graph: regional ventilation distribution in selected ROIs in time. The colors of the curves correspond with the color coding of PEEP levels in the second graph from the top.

that follow each other, discontinuities in the impedance waveform were observed when baseline frames were chosen independently for each measurement as depicted in Fig. 4.

III. Discussion

The main findings of the study are that selection of the baseline frame for fEIT data reconstruction has a minor effect on evaluation of ventilation distribution using ROIs whereas it has a substantial effect on evaluation of EELI and thus EELV.

There are small differences in the distribution of ventilation among ROIs when various baseline frames are selected for reconstruction of fEIT data. These differences might be statistically significant, but their magnitudes are in the order of units of percents. These magnitudes are typically smaller than the natural fluctuation in breath-to-breath results provided by the EIT system (see the bottom graph in Fig. 2) and their values are at the edge of clinical significance. Therefore, neglecting of these differences does not affect clinical interpretation of the calculated regional distribution of

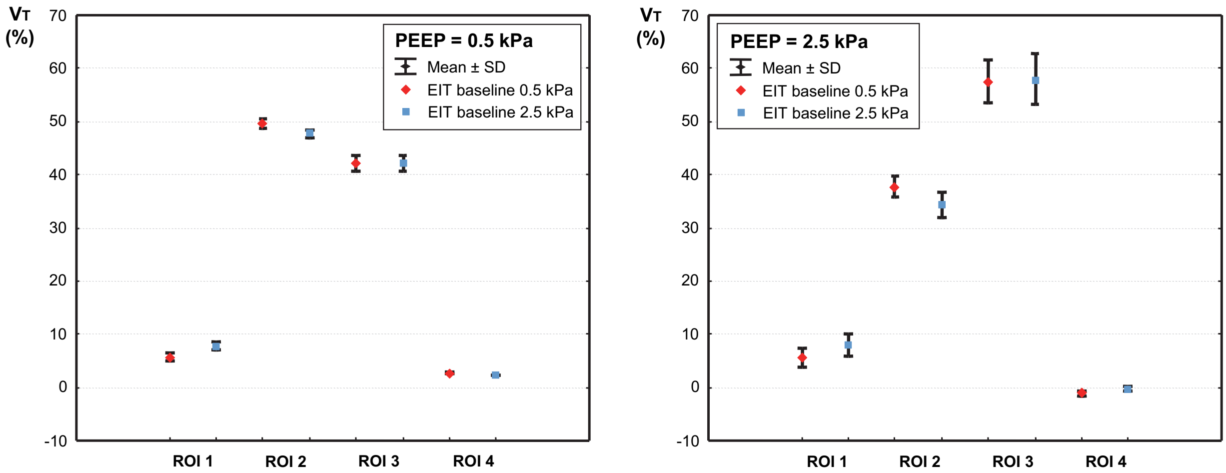

Fig. 3. Comparison of ventilation distribution at two selected PEEP levels (left: PEEP = 0.5 kPa, right: PEEP = 2.5 kPa) calculated from the data that were reconstructed using two baseline frames from different PEEP levels (red: 0.5 kPa, blue: 2.5 kPa).

ventilation. As a result, automated selection of the baseline frame, typically within a segment of EIT data currently analyzed and displayed by the EIT system, may be employed. This makes the evaluation easier without negative influence upon clinical interpretation.

On the other hand, when a long-time evaluation of the EELI (and thus EELV) is desired or when a comparison of two or more segments of EIT records is required, all the evaluated and compared segments should be reconstructed using an identical baseline frame.

The study was performed using the data from three animals. We do not consider this number as insufficient because the studied effect is caused by the reconstruction algorithm and the results were consistent for all pigs.

IV. Conclusion

EIT is an interesting method that can offer real time information about ventilation of lungs. Nevertheless, as EIT is not in fact a true imaging modality, the provided information is dependent on the quality and the way of processing.

Selection of the baseline frames at different PEEP levels results in different values of global TV and EELI. Thus, when estimating V_T and EELV by means of fEIT, it is necessary to choose one common baseline frame for data reconstruction. However, the effect on the percentage values that express the distribution of regional ventilation is negligible and below clinical significance.

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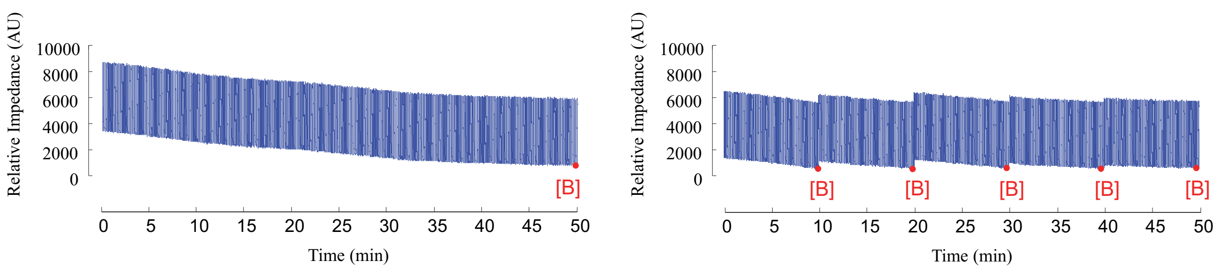

Fig. 4. The effect of baseline setting in a long-term EIT monitoring. Left: one common baseline frame (marked as [B]) was used for the reconstruction of several measurements. Right: each of the measurements was reconstructed using its own baseline frame.

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