Chest Electrical Impedance Tomography and Its Clinical Applications

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Abstract— **Electrical impedance tomography (EIT) has the potential to become a bedside tool for monitoring and guiding ventilator therapy, as well as tracking the development of chronic lung diseases. This paper describes the measurement principle of this novel technique and an overview of the applications of pulmonary EIT in the intensive care unit, including monitoring of ventilation and ventilator-induced lung injury, EIT-guided lung-protective ventilation and pulmonary perfusion. Limitations that hinder EIT to become a routinely used tool in a clinical setting are briefly discussed.**

Keywords— **Electrical impedance tomography, ventilator-induced lung injury, lung-protective ventilation, pulmonary perfusion.**

I. INTRODUCTION

Electrical impedance tomography (EIT) is a non-invasive, radiation-free monitoring imaging technique. The idea of EIT was introduced in mid-1980s by Barber and Brown [1]. Early EIT systems had poor sensitivity and were susceptible to signal interference in clinical settings. After 30 years of developments, both instrumentation and reconstruction algorithms have been intensively improved. Nowadays, EIT becomes one of the active research fields for various clinical applications. Studies show that EIT has the potential to monitor the cerebral ischaemia, stroke or intracranial hemorrhage [2-4], to differentiate malignant from benign regions within the breast [5-6], and to monitor the bladder emptying [7-8]. Among all the clinical applications, the most promising field is chest EIT. It has been proven that EIT can be used as a bedside tool for monitoring and guiding ventilator therapy [9-10], as well as tracking the development of chronic lung diseases [11-12]. A few years ago, first EIT devices became commercially available on the market. After decades of developments, now it is a critical time for this technique, to turn laboratory researches to daily clinical practices. The aim of this paper was to introduce the measurement principle and clinical applications of chest EIT.

II. BASIC PRINCIPLE AND MEASUREMENT

EIT measures the electrical potentials at the chest wall surface based on the phenomenon that changes in regional air content and regional blood flow modify the electrical impedance of lung tissue [13-14]. Before measurement, electrodes are places around the thorax in the fifth intercostal space and one reference electrode is placed at the patients' abdomen. The placement of the electrode planes may vary according to the regions of interest. However, the correlation between impedance and volume changes may be different [15]. Typical chest EIT systems inject alternating currents at a single frequency, ranging from 50 to 150 kHz, through chest wall surface. The number of electrodes, current injection and voltage measurement patterns may vary depending on the application fields. Typical chest EIT devices facilitate 8, 16 or 32 ECG electrodes and use adjacent pattern for both current injection and voltage measurement. Taking 16-electrode system for example (Fig. 1), current injection through one adjacent electrode pair (e.g. electrodes No. 1 and No. 2) results voltage changes at chest wall surface, which are measured by the rest of 13 electrode pairs (excluding the current injection electrodes). Subsequently, the next adjacent electrode pair (e.g. electrodes No. 2 and 3) is used for the next current application and another 13 voltage measurements are performed. The location of the injecting and measuring electrode pairs successively rotates around the entire thorax. One complete rotation results 208 voltage values, and these values are used to reconstruct one cross-sectional EIT image, which is also called a frame.

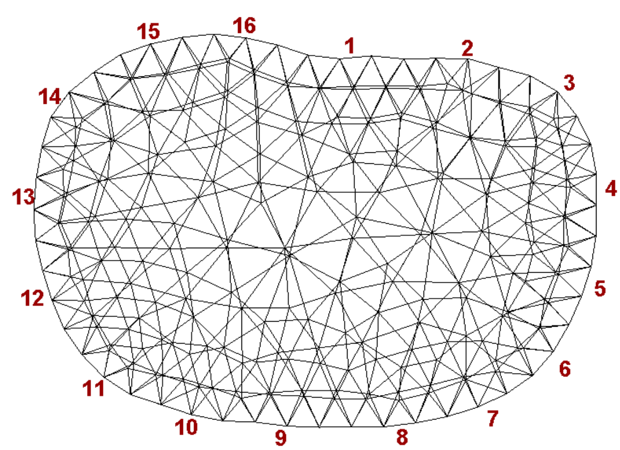

Fig. 1 Finite element model of a patient thorax (cross-sectional) and the electrode positions. Ideally, the electrodes should be placed at equal distance obliquely or in one transverse plane.

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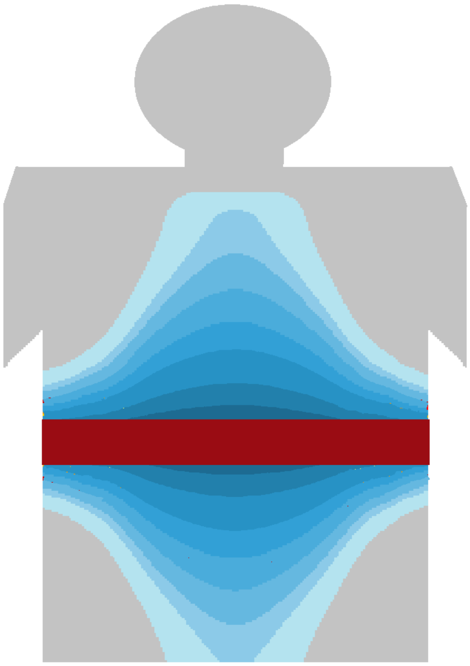

Fig. 2 The relative vertical sensitivity of EIT measurements as a function of the position above and below the electrode plane. Color intensity (grey = 0) corresponds to sensitivity. Same color regions have equal sensitivity. Red band indicates the electrode plane. Y-axis: anteroposterior distance from electrode plane in centimeter; x-axis: lateral distance in centimeter.

Since the electrical current is not going through the thorax in a straight line (different from x-ray), the cross-sectional EIT image that we reconstruct contains the lens-shaped intra-thoracic volume whose bioimpedance changes contribute to the generation of EIT images (Fig. 2). The thickness of the measurement plane increases towards the central region of the thorax. The contribution of impedance changes is reduced with increasing distance from the electrode plane. Therefore, EIT measurement at one plane will not cover the whole lungs, but it is much more than just one thin layer like CT scan.

Most of the EIT systems calculate time-difference relative impedance changes. That means the impedance value at current time point is not an absolute value. Instead, it is subtracted from a value at pre-defined baseline. In this way, image reconstruction errors due to electrode positions, unbalance of contact impedance etc. can be minimized (the idea is similar to instrumental amplifier).

III. Clinical Applications in Intensive Care Unit

Patients in intensive care unit (ICU) often require support from ventilators. The lung status of these patients is one major concern and key factor that influence the ICU discharge. Except EIT, there is no well-established bedside tools that can monitor regional ventilation distribution and thereby evaluate the efficiency of interventions. In the following, we are going to discuss some of the most frequent EIT applications in ICU.

A. Monitoring of Ventilation and Ventilator-Induced Lung Injury

Inappropriate setting of ventilator may introduce injury to the lung, including atelectrauma (collapse and reopening of alveoli), barotrauma and volutrauma (lung tissue over-distended at high pressure) [16]. Due to the high temporal resolution of EIT, dynamic information within a breath can be captured. Regional ventilation delay was proposed with low-flow inflation maneuver to reveal the late "opening" of lung units that collapsed during expiration [17-18]. Lowhagen *et al.* have found that Slow moderate-pressure RM results in lower optimal PEEP and plateau pressures [19].

Figure 3 shows one kind of functional EIT images that highlighted the regions of overdistension, recruitment and tidal recruitment. A lavaged pig was mechanically ventilated with pressure-controlled mode. During an incremental PEEP trial (positive end-expiratory pressure; starting from 1^{st}, PEEP = 5 cmH_2O to 7^{th}, PEEP = 35 cmH_2O), more and more regions are recruited compared to the first PEEP level (purple regions in the functional EIT images in the first two columns; the order of the subfigures are indicated by the solid line with arrow). Regions of overdistension increase with increasing PEEP levels (blue regions). No tidal reopening regions were found at high PEEP levels (white regions). During decremental PEEP trial (starting from 7th to 13th PEEP levels), regions of overdistension decrease. There are no regions collapsed at 13th PEEP level (few purple regions at 7th PEEP level), which indicates an efficient recruitment maneuver.

B. EIT-Guided Lung-Protective Ventilation

Many EIT-based indices were developed to indicate heterogeneity of ventilation distribution [9], center of ventilation [10] and to optimize regional compliance [20]. With these indices, EIT may be used in automated ventilation algorithms to determine the necessity of lung recruitment maneuvers and the sufficiency of PEEP levels. Regional pressure-volume (impedance) curves can be used to determine regional upper inflection points [21]. By evaluating the distribution of ventilation, Mauri *et al.* found out that sighs reduce strain and ventilation heterogeneity during assisted ventilation in patients with acute respiratory distress syndrome [22].

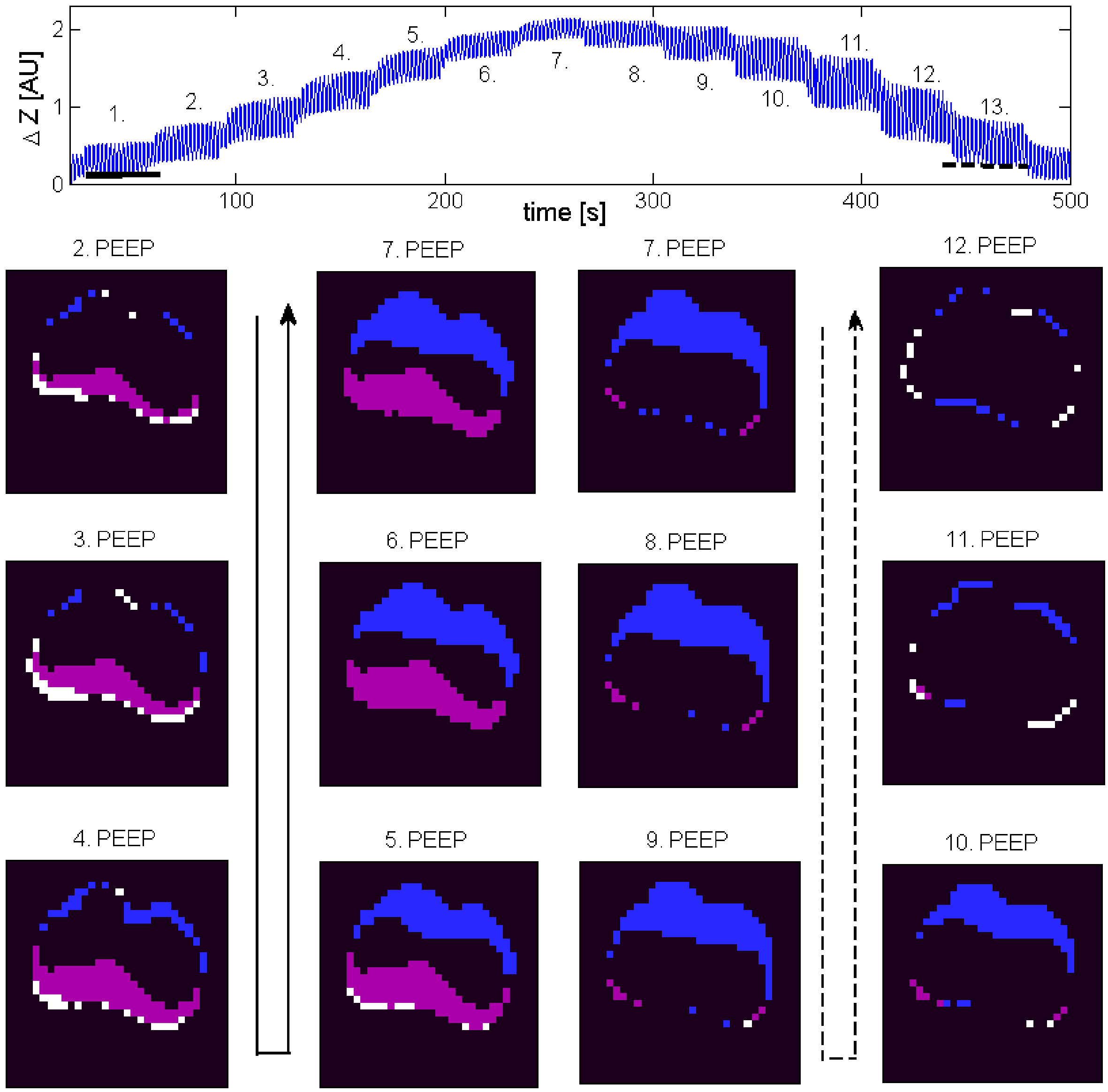

Fig. 3 PEEP titration and the corresponding functional EIT images at each PEEP steps. (unpublished data; measured with Pulmovista 500, Draeger Medical; processed with MATLAB). Top: global impedance waveform during the incremental and decremental PEEP titration. Left (first two columns): functional EIT images during incremental PEEP. Purple regions are recruited regions at the current PEEP step compared to the 1. PEEP step. Overdistension regions are marked in blue and intra-tidal recruited/derecruited regions are indicated in white. Right (last two columns): functional EIT images during decremental PEEP. Purple regions are recruited regions at the current PEEP step compared to the 13. PEEP step. Overdistension regions are marked in blue and intra-tidal recruited/derecruited regions are indicated in white.

High frequency oscillatory ventilation (HFOV) is considered as one of the lung protective strategies. However, respiration rate up to several hertz makes the ventilation distribution during HFOV a mystery to the physicians. Previous studies suggest that EIT is able to assess regional lung volume distribution during HFOV [23-24]. Figure 4 shows the ventilation distribution in one pig during HFOV (Fig. 4 left; mean airway pressure of 30 cmH$_2$O) and conventional ventilation (Fig. 4 right; PEEP = 21 cmH$_2$O). Since two data sets had different reference frames, the amplitudes of the EIT waveforms are not comparable. The ventilation distribution during HFOV is similar to that during conventional ventilation with less overdistension in the gravity non-dependent regions.

Besides, prone position demonstrates also lung protective effects. Changes of ventilation distribution from supine to prone position can be monitored with EIT [25-26].

C. Pulmonary Perfusion

Cardiac-related impedance changes are much smaller than ventilation-induced impedance changes. Nevertheless, EIT can capture the cardiac-related impedance changes as well, by applying ECG-triggered or breath-hold measurement, or by frequency domain filtering [27-28]. The signal is not directly related to stroke volume but more to vessel pulsations. High conductivity of hypertonic saline makes it suitable for an electric contrast agent and increases the amplitude of cardiac-related impedance changes. Borges and his colleagues injected hypertonic saline in the right atrium and performed a first-pass kinetics analysis [29]. They found that the distribution of pulmonary blood flow as assessed by EIT agreed well with the one obtained by single-photon-emission computerized tomography.

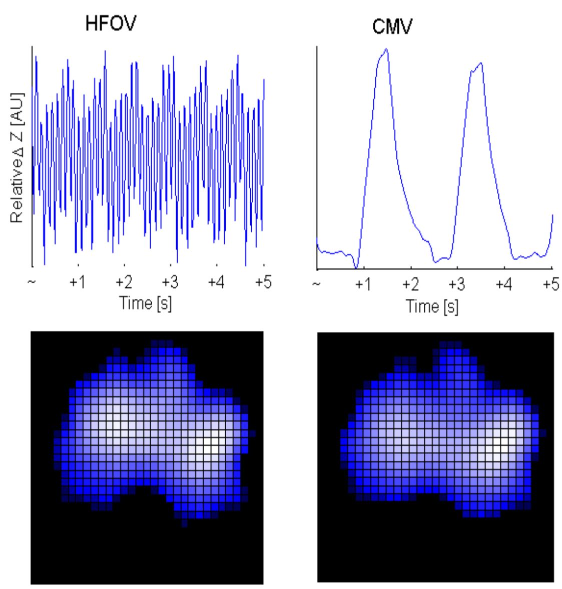

Fig. 4 comparison of ventilation distribution during left, high frequency oscillatory ventilation (HFOV) and right, conventional mechanical ventilation (CMV) in a lavaged pig (unpublished data). Global relative impedance waveforms of 5 seconds of each period are showed. Since the baseline of these two data sets are different, the amplitude of the relative impedance values are not comparable.

IV. Limitations and Future Developments

New users often compare EIT to imaging techniques that they are familiar with, such as computed tomography (CT) and magnetic resonance imaging (MRI). They might not be satisfied with the limited spatial resolution of EIT. Indeed, no anatomical structures can be recognized in an EIT image. However, with up to 50 Hz temporal resolution, EIT should be considered as a functional imaging technique that captures different information as CT and MRI [30]. Unable to measure absolute impedance values and unable to cover the whole lungs during one measurement are two major limitations of EIT, which require a lot of experiences in data analysis and interpretation. Simultaneous EIT measurements at different cross-sectional planes might be developed in the future as a single device.

In order to make EIT as a routine clinical practice, standardizing EIT measurements for various clinical scenarios is urgently required.

A large number of EIT studies on clinical applications and diseases were published in the past decades. With respect to applicability, time and radiation exposure, EIT may represent a promising supplement for X-ray and CT in the future.

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Conflict of Interest

Zhanqi Zhao receives a consulting fee from Dräger Medical. Knut Möller declare no conflict of interest.

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