Multi-frequency EIT in Acute Lung Injury

Differences in multi-frequency EIT imaging in an animal model of acute lung injury

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***Abstract*—Up to date, acute lung injury is still a critical disease with a high mortality rate necessitating mechanical ventilation. Although development of protective ventilation strategies has been the subject of numerous studies in the last years, measurement and monitoring of their clinical results is still challenging and in large parts practical methods are unavailable. Both, pathophysiologic issues of the disease and effects of therapeutic interventions often occur delayed and are therefore difficult to detect. Besides, existing methods can either display global effects with low sensitivity for specific pathologies or otherwise bed-side application is not feasible. Electrical impedance tomography is therefore a very promising technique facilitating non-invasive bed-side applications for regional ventilation monitoring and further purposes. In addition to diverging electrical dispersions of various tissues also their changes according to specific pathologies play a decisive role. After the induction of an acute lung injury by surfactant depletion in a porcine model of lung injury, changes of dispersion were observed. For image acquisition, a Goe-MF II EIT system with provided standard software was used at several frequencies between 44 and 195 kHz in sequence. Regarding tidal variation of summarized electrical impedance, the signal rose with increasing frequency. In this way, probably a more accurate differentiation of certain pathologies can be obtained in future studies.**

Keywords-Acute lung injury; mechanical ventilation; lung protective ventilation; tissue dispersion; lung edema; multifrequency EIT.

I. INTRODUCTION

Acute lung injury (ALI) is characterized by a severe respiratory impairment. As a result, an insufficient oxygenation necessitates mechanical ventilation. Since the application of positive pressures is not physiological, this can further harm the lung tissue [1]. The Acute Respiratory Distress Syndrome (ARDS) is the most serious form of ALI showing a current mortality of 43 % [2]. The pathophysiological key problem is the occurrence of marked atelectasis and lung edema in dorsal parts of the lungs due to gravity effects [3].

Several strategies for lung protective ventilation were already explored. Basically, it is important to avoid cyclic opening and closing of alveolar structure which is accompanied by a biotrauma triggering inflammatory responses. Therefore, an adapted positive end-expiratory pressure (PEEP) has to be chosen which keeps collapsed alveoli partially opened. Although studies failed to show significant effects on mortality rates, at least oxygenation was improved and the duration of mechanical ventilation was decreased [4].

Furthermore, it is uncontroversial that limitation of tidal volumes to 6 ml kg^{-1} bodyweight and of maximum inspiratory pressure to less than 30 mbar should be achieved [5]. Anyhow, because of the heterogeneity of lung injury, some regions are already hyper-inflated when other ones are not even ventilated.

Thus, optimization of respiratory settings requires continuous inquiry and examination of relevant outcome parameters. However, available methods are either too unspecific like blood gas analysis or too expensive and unpractical like computer tomography imaging. Besides, all current techniques display effects with a relative high time delay.

Electrical Impedance Tomography (EIT) has the potential to become a standard monitoring technique for intensive care medicine. It offers non-invasive real-time imaging without radiation, availability at bedside and a high demand interval.

Numerous trials already studied clinical feasibility of EIT and adequacy for several medical applications. Especially, effects of PEEP settings on regional impedance variation were pointed out. From already established methods like CT it is known that atelectasis in dorsal regions can be partially recruited by an adequate PEEP which therefore leads to a more homogenous air distribution. These effects can also be monitored by EIT.

Up to date, most studies solely focused on tidal variation of electrical impedance at one defined frequency (e.g. 50 kHz). The aim of our project was to combine information about dispersion of tissue (especially differences between "healthy" and "diseased" lung) and morphologic properties by using several frequencies in order to examine the current state of injury.

II. MATERIAL AND METHODS

A. Animal modell

The experimental protocol was approved by the responsible governmental institution (8.87-51.04.2010.A120). Eight pigs were anesthetized and mechanically ventilated (volume-controlled, tidal volume of 6 ml/kg body weight, FiO_2 1.0, PEEP of 5 mbar). An arterial catheter (Vygon, Ecouen, France) and an 8.5-F venous sheath (Arrow Deutschland GmbH,

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Erding, Germany) were percutaneously advanced into a femoral vessel. A Swan-Ganz catheter (Arrow Deutschland GmbH, Erding, Germany) was flow-directed into a pulmonary artery under pressure-guidance.

B. Data acquisition

Hemodynamics were assessed by routine clinical monitoring measuring heart rate, mean arterial and pulmonary artery blood pressures, central venous pressure, cardiac output and pulmonary capillary wedge pressure. Respiration parameters were read from the ventilator. Respiratory gases (p_aO_2, p_aCO_2) were measured from blood samples with standard blood-gas electrodes (ABL 510, Radiometer, Copenhagen, Denmark).

For performing EIT (Goe-MFII EIT system, Dräger medical, Lübeck, Germany), a 16-electrodes belt was fixed circularly around the thorax in projection of the 4^{th}-5^{th} rib. Briefly, alternating currents (5 mA, 83 kHz) were fed in adjoining electrode pairs and subsequently resulting voltages were measured in pairs around the thorax. The software provided by Dräger reconstructs 32x32 pixel sized images with 13 fps in real-time. Reconstructed images and raw data were recorded for post-hoc analysis. For studying differences in images concerning the applied frequency, in several pigs multiple frequencies were used sequentially from which the following were analyzed this paper: 44, 83, 127 and 195 kHz.

C. Study protocol

Three time points were predetermined for data collection including vital data, respiratory parameters, blood samples and EIT recording. First, baseline measurements were obtained from all groups. Then, experimental ALI was induced by repeated surfactant washout, as described previously [6]. When a predefined arterial oxygen tension (p_aO_2) <100 mmHg was achieved and persisted for ≥60 min without additional lavages, "ALI measurements" were carried out. No further intervention was done. Another set of data was collected one hour afterwards ("post-ALI") for comparison purposes. After completion of the protocol, animals were euthanized under deep analog-sedation.

D. EIT analysis

Regarding evaluation of EIT, tidal variation (TVEIT) imaging was used [7]. For each recorded ventilation cycle, the image of minimal summarized (global) impedance $\min(z_g)$ is subtracted from the maximal one $\max(z_g)$. In order to reduce background noise and reconstruction artifacts, pixels with intensities of less than 10 % of global maximum were set to zero. Four equal sized regions of interest (ROI), ROI_1 to ROI_4 located from ventral to dorsal lung regions comprising the whole lung during inspiration, were defined at one-time for all measurements and animals. Regional tidal variances ($TVEIT_1$ to $TVEIT_4$) are represented by the sum of impedance changes in ROI. In order to quantify shifts in ventilation (e.g. from dorsal to ventral, in consequence of atelectasis), regional impedances summed over ROI_1 to ROI_4 were calculated [8].

Furthermore, TVEIT images of the used frequencies were compared. Firstly, center of electrical impedance for the left and right lung and their distance were calculated separately (z_{CL}, z_{CR}) by using (1) after interpolation of the 32x32 pixel TVEIT matrix to 320x320 pixels.

$$x_s = \frac{\frac{1}{2}\sum_a^b f(x)\cdot x\,dx}{\sum_a^b f(x)\,dx}; \qquad y_s = \frac{\frac{1}{2}\sum_a^b (f(x))^2\,dx}{\sum_a^b f(x)\,dx} \tag{1}$$

In this formula, the coordinates of the center of impedances are given by x_s and y_s, where $f(x)$ represents the impedance at location x, a the left, b the right discrete limit of the structure, e.g. the left or right lung. Secondly, global signals were calculated by summing up all pixels of TVEIT images. Global signals as well as positions and distances of center of impedances were compared concerning the distinct frequencies mentioned above. Calculations and analysis were performed with MATLAB R2011a (The MathWorks Inc., Natick, MA, USA).

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III. Results

At baseline, no oxygenation and hemodynamic parameters were in a physiologic range since all animals were healthy. After induction of ALI, oxygenation significantly worsened and $paCO_2$ increased. Consequently, significantly higher values were reached for peak inspiratory pressure and respiratory rate after ALI.

Frequency	Healthy lung		ALI	
	ΔC_{lat}	ΔC_{AP}	ΔC_{lat}	ΔC_{AP}
44 kHz	14.1	4.1	10.5	3.5
83 kHz	12.9	3.8	10.6	3.4
127 kHz	14.1	4.1	10.7	3.3
195 kHz	18.9	8.1	11.1	2.9

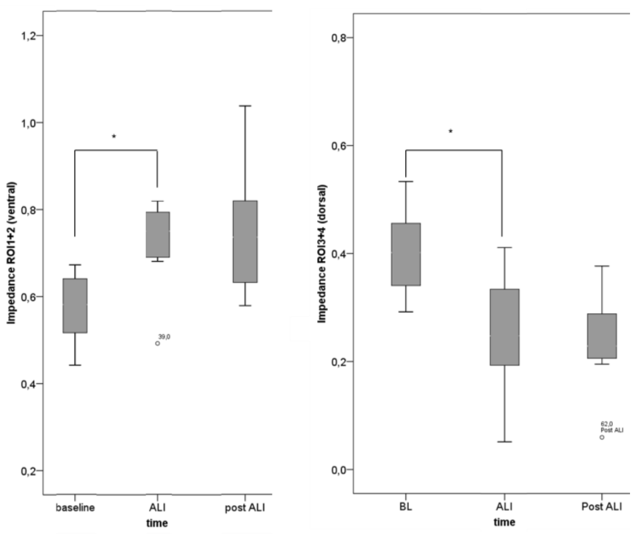
Table 1: Centers of impedance were calculated for both lungs and their coordinates were subtracted. The difference concerning the lateral axis is ΔC_{lat}, for anterior-posterior it is ΔC_{AP}.

The application of the threshold as described in the methods section was adapted to reduce the ground noise and reconstruction artifacts. As already published (e.g. [8]), after ALI, an increased signal was obtained from the ventral parts since in dorsal parts atelectasis occur – sum of impedance in ROI3 and 4 were decreased and in ROI1 and 2 increased (figure 1).

Center of impedances were calculated for both lungs and afterwards their distance was computed for each frequency. For both situations, healthy and ALI, an increase of lateral distance with ascending frequency was pointed out (table 1). The morphologic distinguishability of mediastinum and lungs were better for high frequencies (figure 2).

Interestingly, the global sum of impedance variation increased monotonous with frequency for ALI but not under healthy conditions (figure 3).

FIGURE 1: SHIFT OF REGIONAL IMPEDANCE VARIATION



Regions of interest (ROI) 1 and 2 represents the ventral parts of the lung, ROI 3 and 4 the dorsal ones. The decreasing signal in dorsal parts corresponds to occurring atelectasis after the induction of acute lung injury. *p<0.01 (t-test, paired groups)

IV. DISCUSSION

In the present study we examined effects of acute lung injury to EIT tidal variation imaging. As already published by other groups and also by the authors themselves, a shift of regional impedance variation from dorsal to ventral during ALI occurred. Additionally, the influence of ALI to the dispersion of lung tissue was studied. Interestingly, several differences regarding resulting images were obtained.

During the acquisition, signal processing and image reconstruction artifacts are not totally avoidable. In order to optimize image quality the consideration of anatomic pre-information is a quite adequate way. One very easy way is to apply a certain threshold under which all signals are set to zero.

Apart from the effects of dorsal atelectasis to TVEIT images, the project focused on the lung tissue dispersion. A relatively high range of dispersions concerning various tissue types and also between deflated and inflated lung is known from literature [9]. Therefore it is interesting to examine the impacts of lung pathologies like edema and atelectasis on EIT by using several frequencies. It was questionable whether there is a difference in impedance signals due to the relatively small frequency range. Besides, TVEIT imaging as used, so no absolute impedance measurements but just differences to a reference were obtained. Nevertheless, we noticed that (1) for acutely injured lungs total tidal impedance variation increased with frequency under ALI and (2) centers of impedance for the left and right lung moved farer apart.

Reasons for an increased global impedance variation can be associated with both altered end-inspiratory and end-expiratory tissue dispersion. As a matter of fact, the so-called b-dispersion is sensitive to cellular and tissue morphology especially to intra- and extracellular membrane structures. For lower frequencies, charging and discharging of cell membranes leads to a higher capacitive reactance. Therefore a higher current through the extracellular compartment occurs. With higher frequency, capacitive reactance decreases and current flow changes. As a consequence, with higher frequencies, intracellular and membrane structural changes can be detected more precise. During ALI, a higher part of atelectasis and edema as well as further cellular morphological changes are present. Hence, a reduced capacitive reactance with increased current flows through intracellular spaces can be assumed especially for end-expiration state. During inspiration, lung properties are mainly influenced by inflated air - therefore we expect fewer differences between healthy and injured lungs.

“Moving” centers of impedance for the right and left lung with frequency are to be explained with different dispersions of mediastinum and lung tissue.

In future studies, varied dispersion of injured and healthy lung tissue should be taken into account. It is crucial to examine diverging electrical properties of lung pathologies in order to improve the sensitivity of EIT devices for diagnostic purposes.

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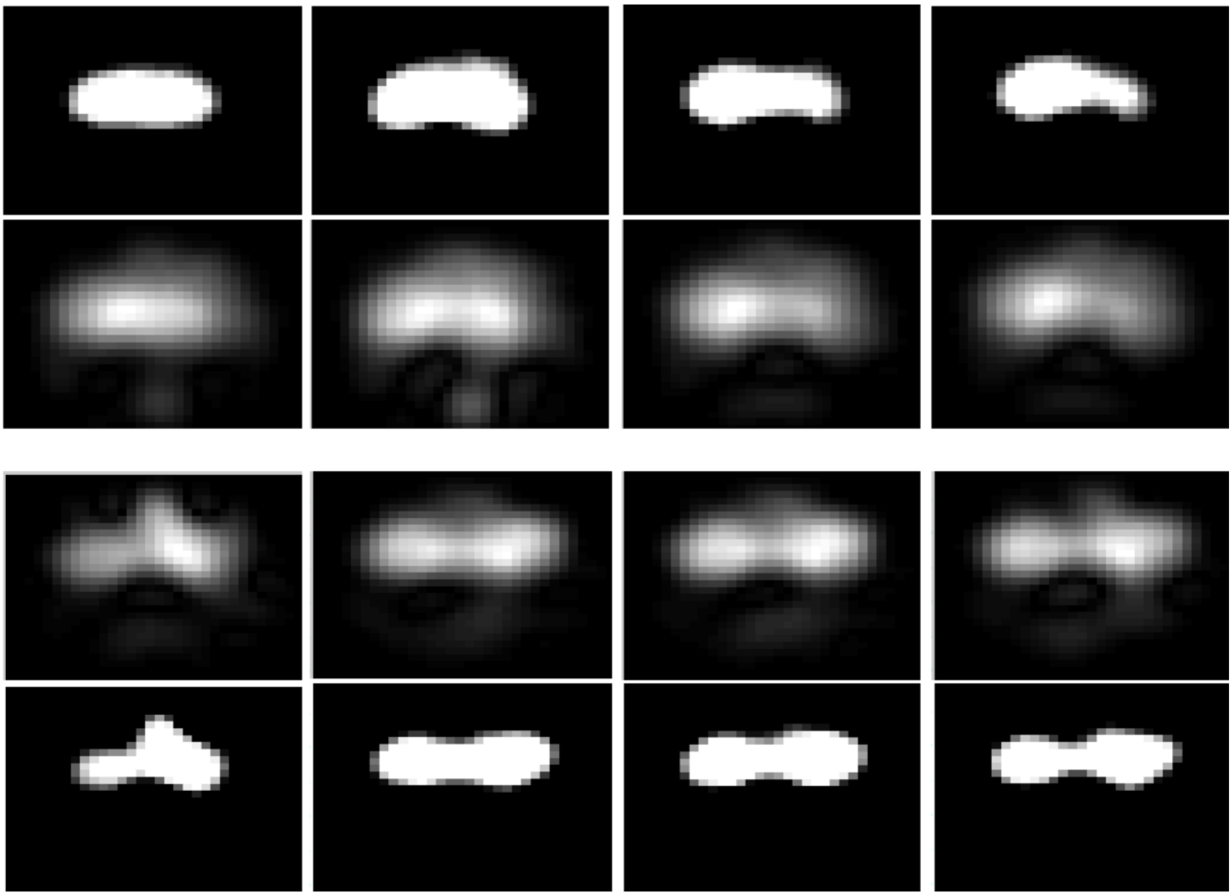
FIGURE 2: TIDAL VARIATION EIT IMAGING OF HEALTHY AND ACUTELY INJURED LUNGS



Effects of various applied frequencies (from left to right: 44, 83, 127 and 195 kHz) in EIT of healthy (upper rows 1 and 2) and acutely injured pigs (lower rows 3 and 4). Morphologic differences were detectable concerning the distinguishability of lungs and mediastinum. Center of electrical impedance of each lung seems to drift apart from each other with increasing frequencies.

FIGURE 3: GLOBAL IMPEDANCE IN RELATION TO APPLIED FREQUENCY