Synchronous absolute EIT in three thoracic planes at different gravity levels

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Abstract. The validity of absolute Electrical Impedance Tomography (a-EIT) for assessment of local lung volume has been investigated far less than the well evaluated ventilation monitoring by functional EIT (f-EIT). To achieve progress in a-EIT we investigated 10 healthy volunteers in an upright sitting position by using a-EIT at normal gravity (1 g), weightlessness (0 g) and approx. double gravity (1.8 g) during parabolic flight manoeuvres. Lung resistivity in three thoracic planes was determined by a-EIT using a multiple-plane synchronised Goe-MF II EIT system. Tomograms of resistivity at end-expiration in normal spontaneous breathing were reconstructed by a modified SIRT algorithm. Local lung resistivity was determined separately for both lungs. The respective resistivity values at 1 g and 1.8 g before and after weightlessness show an almost reversible behaviour along the sequence of gravity changes with a tendency to be lower after occurrence of weightlessness. The results reveal not only the expected varying resistivity of lung tissue in cranio-caudal direction but also a clear difference in these cranio-caudal stratifications of local lung volume between the left and right lung. The resolution and stability of absolute EIT seem to be valid and expressive for future investigations of unilateral lung volume under different physiological and pathological conditions.

1. Introduction

Aeration and ventilation of the lung are not homogeneously distributed. The relations of these properties have been investigated formerly by elaborate methods, e.g. [1], [2]. In the healthy lung the cranio-caudal distribution is expected to be in accordance to the lung model of West [3], [4]. That means the upper lung regions will contain more air than the lower ones due to the gravity dependent gradient of the transpulmonary pressure. We investigated this distribution of aeration in the human lungs by extending the usage of normal CE-certified EIT devices (Goe-MF II type) to synchronous operation in three thoracic planes. We thereby avoided any hardware modifications that would have resulted in a long-lasting new CE-certification process for human application. The resistivity values of lung tissue determined by absolute EIT (a-EIT) were the target as a measure for the quantification of lung tissue aeration. In this study the feasibility and meaningfulness of this approach using a-EIT was tested and compared to the lung model of West by changing the level of gravity.

2. Methods

2.1. Realisation of synchronous multiple plane operation of the Goe-MF II EIT systems

Three EIT systems of the Goe-MF II type were used for measurements in three thoracic planes. The CE-certified EIT systems (for use on humans) are controlled by the bidirectional Universal Serial Bus
(USB) which is per se poorly real-time capable. Due to the non-deterministic occurrence of latencies in the operation of multiple EIT systems which are controlled exclusively by USB the following concept was applied to ensure sufficient synchronous operation of the EIT devices: A timestamp is sent from the host computer to all clients (EIT-systems) and the difference in time between each EIT system and the host computer is continuously determined by a sliding average. The value of this deviation is used to speed up or slow down the internal clock in each client which is controlled by a voltage controlled crystal oscillator (VCXO). The entire design is basically realized as a digital proportional-integral (PI) controller in each EIT system. It is important to achieve a nearly identical relation in time between the three EIT systems whereas the absolute difference in time between the host computer and the EIT systems is not of relevance. After an initialisation phase the entire arrangement is locked in a fixed phase relationship between the attached EIT systems. Therefore a synchronised control of the interleaved measurement procedure in all of the three EIT systems is possible in a very flexible manner. The software ensures this state of operation and displays quantitatively the remaining tiny differences of the timing jitter.

2.2. EIT measurements and data evaluation
We investigated 10 healthy volunteers (7 male and 3 female, mean body weight 76.3 kg ± 14.5 kg SD, age between 19 and 60 years) in an upright sitting position by using a-EIT under conditions of changing gravity between weightlessness (0 g) and approx. double gravity (1.8 g) during parabolic flight manoeuvres. Parabolic flight manoeuvres were performed by an Airbus A 300 operated by NOVESPACE (France) during the 18th Parabolic Flight Campan of the German Aerospace Center (DLR). Each of the parabolas results in five consecutive gravity levels of 20 to 25 s duration in the following sequence: normal gravity (1 g before), hyper-gravity (1.8 g before), weightlessness (0 g), hyper-gravity (1.8 g after) and normal gravity (1 g after). Measurements of lung resistivity by a-EIT were carried out synchronously in three thoracic planes. The middle plane was located at the level of the xiphoid process and the cranial and caudal plane 5 to 6 cm above and below the middle plane. A multiple-plane synchronised Goe-MF II EIT system (see above) was used. The total frame rate was 6.6 Hz (interlaced operation of the three systems) and the injection current 5 mA_{eff} at 50 kHz for all measurements. Lung tissue resistivity, which is considered to be linearly correlated to local lung volume (air content) [5-9], was quantified by a-EIT at end-expiration in normal spontaneous breathing. The absolute tomograms were reconstructed by a modified SIRT algorithm [10], [11] whereas resistivity was quantified for the total lung and separately for both lungs. The location and number of the pixels (regions of interest [ROIs] for a-EIT) that usually represent the areas of the lungs in healthy volunteers were determined by f-EIT. They were used as predefined and fixed ROIs for all volunteers. Statistical analysis was performed applying a paired t-test for the differences between the right and left lung and the effect of gravity was tested using a one way ANOVA for repeated measures.

3. Results

3.1. Methodological results
After switch-on, a short synchronisation phase was needed to achieve a stable and synchronous operation of the three EIT systems. The application of the described synchronisation concept resulted in a timing jitter of always less than 100 µs between the three EIT systems. The applicability of the experimental approach and setup under the conditions of changing gravity during parabolic flights was successfully demonstrated. Based on the synchronous raw data from three different thoracic planes it was possible to calculate the intrathoracic stratification of resistivity values in cranio-caudal direction under the dynamic conditions of spontaneous breathing. Also a clear separation of the resistivity values of lung tissue - being mainly dependent on lung aeration - between the right and the left lung was achieved by the applied SIRT algorithm.
3.2. Physiological results

Figure 1 displays the resistivity values in the three thoracic planes of the total lung (left panel), the left lung (middle panel) and the right lung (right panel) (mean ± SE) in the course of the different gravity levels as they occur during a parabolic flight manoeuvre. The resistivity at 0 g is always lower than that at 1 g and 1.8 g in all planes. A significant influence (p<0.05) of gravity compared to 0 g is denoted by *. Stratification from higher resistivities (top plane) to lower ones (bottom plane) is observed in both lungs whereas it is more pronounced in the right lung. For all gravity levels the resistivity of the right lung in the bottom plane (black line, bot) is significantly (p<0.05) lower than that of the left lung. In the middle (mid) and top (top) plane a higher variation of individual resistivities is observed compared to the bottom plane.

![Resistivity of the total, left and right lungs in three thoracic planes in the course of parabolic flight manoeuvres (mean ± SE). A significant influence (p<0.05) of gravity compared to 0 g is denoted by *.

The respective resistivity values at 1 g and 1.8 g before and after weightlessness were averaged for each of the planes since they show an almost reversible behavior along the sequence of gravity changes with a tendency to be lower after occurrence of weightlessness. In detail, the corresponding values for the cranial, middle and caudal plane in the right lung are: 6.48 Ωm, 5.36 Ωm and 4.61 Ωm at 1 g; 6.48 Ωm, 5.50 Ωm and 4.74 Ωm at 1.8 g and 6.14 Ωm, 4.93 Ωm and 4.29 Ωm at 0 g. In the left lung the respective resistivities are: 6.35 Ωm, 5.95 Ωm and 5.25 Ωm at 1 g; 6.42 Ωm, 6.13 Ωm and 5.36 Ωm at 1.8 g and 6.11 Ωm, 5.43 Ωm and 4.85 Ωm at 0 g.

4. Discussion

The concept of synchronising existing CE-certified single plane EIT systems via USB is modular and extendible to a useful number of EIT systems operating in parallel. It offers more flexibility by firmware and software adaptation than a simple extension to a multiple plane operation by multiplexing the analog front end of an EIT system. This concept allows also current injection in one plane and a simultaneous measurement of the resulting potential differences in all of the other planes. But this option has not been used in the current study.

The resistivity range (cf. figure 1) we found in vivo at expiratory level for the human lungs at 50 kHz fits well to the value of 5.9 Ωm reported by [12] for deflated pig lungs (interpolated between the in vivo measurements at 10 kHz and 100 kHz from figure 7 in [12]). Direct measurements in vivo on human lung tissue have not been performed to our knowledge for ethical reasons. Since resistivity of lung tissue is mainly dependent on aeration resulting in stretching the surrounding tissue of the pulmonary alveoli [13], blood and fluid content will probably play a minor role. But a shift in blood or
fluid content into the lungs may be one of the reasons for the tendency of lower values after weightlessness. The results of stratification of aeration determined by a-EIT for the total lung at end-expiration are in full agreement with those predicted by the lung model of West [2]. a-EIT used in this study is more easily applicable than other approaches that were formerly used to investigate local aeration of the lungs, which is an evident advantage of EIT that may be of interest for future space missions. The physiological plausible results of the total lung are considered to be an indirect validation of the whole methodological setup for synchronous multiple plane a-EIT based on the Goe-MF II hardware and the applied SIRT algorithm. The resolution and stability of a-EIT seem to be valid and expressive.

Looking in more detail at the results of the left and right lungs a different level of cranio-caudal stratification in lung tissue aeration is observed. This is also the case at weightlessness which implies an inherent inhomogeneity of lung aeration.

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