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Impact of artificial airway resistances on regional ventilation distribution during airway closure

Abstract: Electrical impedance tomography (EIT), a non-invasive and radiation-free imaging technique can be used in pulmonary function monitoring for determining regional ventilation distribution within the lung. Gold standard in pulmonary function monitoring is spirometry/body plethysmography, a method using forced breathing maneuvers to obtain global lung function parameters. However, this method is heavily dependent on the cooperation of the patients. Within this observational study, a method under normal breathing was tested with 5 healthy volunteers, which provides regional information about ventilation distribution. The occlusion method Rocc, a method for determining airway resistance, was used to create a short-term airway closure. Regional ventilation during the airway closure was examined with EIT. Simultaneously four different artificial airway resistances were used to simulate airway obstructions. Results show that EIT in combination with the ROcc method is suitable for the detection of regional differences in ventilation during airway closure for all four artificial airway resistances. Although the sum of relative impedances at the end of the shutter maneuver are smaller (nearly -0.100 AU) for the airway resistances Ø 12.5 mm, Ø 10.5 mm and Ø 9.5 mm than for the smallest one with Ø 30.0 mm (~ -0.070 AU), the changes in impedance from the start to the end of the shutter maneuver differs only slightly between the four artificial airway resistances. All impedance changes are in the range of 0.100 to 0.130 AU. The combination of EIT and the ROcc method provides not only global parameters such as airway resistance under normal breathing conditions, but also results of regional ventilation, which could enable the identification of areas affected by airway obstructions. However, the obtained results indicate that EIT might be a useful tool in the diagnosis and follow-up of obstructive lung diseases.

Keywords: Electrical impedance tomography, airway obstructions, artificial airway resistance, regional ventilation distribution, body plethysmography.

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1 Introduction

Due to the increasing number of chronic obstructive pulmonary diseases [1] new examination methods are required. Electrical impedance tomography is a non-invasive, radiation-free, functional imaging technique and can be used in the field of pulmonary function monitoring [2]. This method is suitable for the detection of ventilation and perfusion [3] in the lungs of mechanically ventilated patients in the intensive care unit [4] as well of spontaneously breathing patients with lung diseases as airway obstructions [5,6]. Due to the high temporal resolutions of EIT even short-term changes in ventilation can be detected [7]. The principle of EIT is based on the injection of a small alternating current (5- 10 mA) in the thorax and the measurement of the resulting voltages on the surface. For image reconstruction, measured voltages are converted into relative impedance values by mathematical algorithms. This method is therefore suitable for the detection of impedance changes of the lungs caused by differences in the air content and blood volume during respiration [8]. One of the most used methods in pulmonary function monitoring is the spirometry/body plethysmography – a low cost method to determine the airflow [9]. Forced breathing maneuvers are necessary to obtain parameters that indicate the health status of the lungs. Problematic are the forced breathing maneuvers – children or

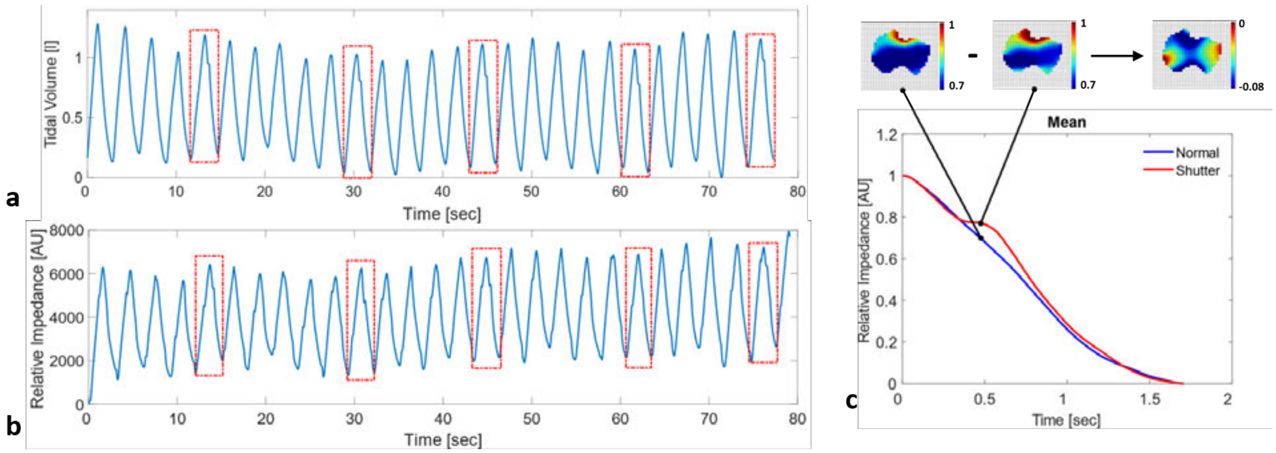

Figure 1: (a) Relative impedance changes during normal breathing using the occlusion method ROcc (b). Calculation of difference images for each timepoint during expiration (c).

patients with severe airway obstructions may not be able to perform them. In the case of airway obstructions, areas of the lungs can be affected to different extents. These affected areas cannot be identified by spirometry/ body plethysmography. A combination of EIT with spirometry/ body plethysmography could be a promising approach to obtain global results as well as regional results [10]. However, forced breathing maneuvers have been used so far for determining the regional ventilation distribution in patients with lung diseases. Therefore, the aim of this study was not only to obtain information about the regional ventilation distribution but also to establish a method under normal breathing which is independent of the cooperation of the patients.

2 Methods

2.1 Study protocol

5 healthy volunteers (2 male, 3 female, 24.8±2.7 years/ 177.0±8.5 cm/ 78.8±12.7 kg) were performing normal breathing in sitting posture in a body plethysmograph (PowerCube®Body+, Ganshorn Medizin Electronic, Germany). Obstructions were artificially induced by various airway resistances (Ø 30.0 mm, Ø 12.5 mm, Ø 10.5 mm, Ø 9.5 mm) attached between the mouthpiece and the spirometer. The occlusion method to calculate the airway resistance (ROcc), a common method in body plethysmography, was used. A shutter can be triggered manually during normal breathing with this method. The shutter was used for the first time after an even tidal volume was detectable. The shutter was triggered at least 5 times for 200 ms (at the beginning of expiration) during each measurement (Figure 1a). After each shutter, the volunteers continued with normal breathing. Each measurement was performed twice for reproducibility. In parallel, EIT-Data were recorded at 3rd intercostal space (frame rate 40 Hz) using a 16-electrode system (PulmoVista®500, Dräger, Germany) (Figure 1b).

2.2 EIT data processing

EIT images with a resolution of 32×32 pixels were generated using the EIT Analysis Tool 6.1 (Dräger, Germany). The following steps were implemented in MATLAB (R2019a, The Mathworks® Inc., Natick, USA). Since the data of the body plethysmograph were recorded with a sample frequency of 200 Hz, the EIT data was interpolated from 40 Hz to 200 Hz. EIT data were filtered with a Butterworth bandstop filter (6th order, cut-off frequencies 55 min^{-1} and 75 min^{-1}) to exclude impedance values caused by cardiac activity. For further analysis steps the lung region was defined and other tissue such as adipose tissue was excluded. For the definition of the lung region, all regional impedance values of the EIT images (32×32 pixels) of end-expiration during normal breathing were subtracted from all regional impedance values of end-inspiration and a functional EIT image with averaged impedance values was created. The maximum impedance value of the functional image was determined and a threshold of 20 % was used. All impedance values greater than 20 % of the maximum value were added to the lung region.

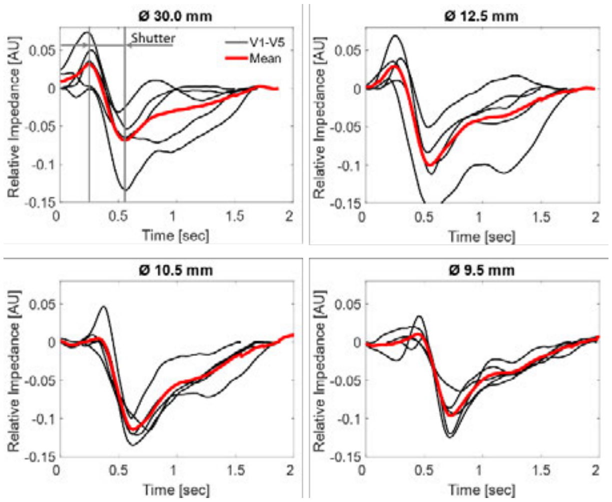

Figure 2: Sum of relative impedance during normal breathing with the four airway resistances Ø 30.0 mm, Ø 12.5 mm, Ø 10.5 mm and Ø 9.5 mm of the five volunteers.

2.3 Data analysis

The bandstop filtered EIT signal was divided into normal breaths and breaths with shutter. A linear trend was subtracted from all normal breaths and breaths with shutter so that each breath begins and ends at an impedance value of zero. For the following steps only the phase of expiration was analyzed, because the shutter was triggered at the beginning of expiration. Since the length of the individual breaths varied, all breaths were interpolated to the time span of the longest breath. The average of all regional values for the normal breaths and breaths with shutter were calculated and scaled to 1. For each timepoint during expiration all regional averaged scaled values of the breaths with shutter were subtracted from the regional values of the normal breaths and difference images (32×32 pixels) were generated (Figure 1c). The sum of relative impedances was calculated in the difference images and normalized to the number of all pixels for each volunteer. Furthermore, the mean value of the sums of relative impedances of all five volunteers was calculated.

Table 1: Mean relative impedance values of all 5 volunteers at the start and the end of the shutter as well as the impedance change over the shutter maneuver for the four airway resistances.

Airway resistance [mm]	Shutter start [AU]	Shutter end [AU]	Impedance change [AU]
Ø 30.0	0.030	-0.070	0.100
Ø 12.5	0.030	-0.100	0.130
Ø 10.5	0.005	-0.110	0.115
Ø 9.5	0.010	-0.100	0.110

3 Results

The time span of the shutter maneuver can be clearly identified in the sum of relative impedances for all five volunteers (Figure 2). All measurements (Ø 30.0 mm, Ø 12.5 mm, Ø 10.5 mm and Ø 9.5 mm) show a decrease in the sum of the relative impedances as soon as the respiratory flow is interrupted. An increase in the sum of relative impedances can be observed at the end of the shutter maneuver. In the mean of the five volunteers' slight differences could be observed between the four airway resistances. With a higher airway resistance, the relative impedance at the end of the shutter maneuver decreases from about -0.070 AU (Ø 30.0 mm) to nearly -0.100 AU (Ø 12.5 mm, Ø 10.5 mm and Ø 9.5 mm). In consideration of the changes in impedance, there are almost no differences for the four airway resistances. All impedance changes are in the range of 0.100 to 0.130 AU (Figure 2, Table 1). Figure 3 shows exemplarily the ventilation distribution within the differences images during the shutter maneuver (a) as well as the relative impedance over time for two selected pixel (b) and the sum of relative impedance in the difference images (c). Ventilation redistribution during the shutter maneuver can be demonstrated for all five volunteers with all four airway resistances. Regional differences between the normal breaths and the breaths with shutter can be identified by taking a closer look at the relative impedances over time of individual pixels. The breaths with shutter show a characteristic shoulder in the beginning of expiration due to the interruption of respiratory flow. With this method, both global parameters

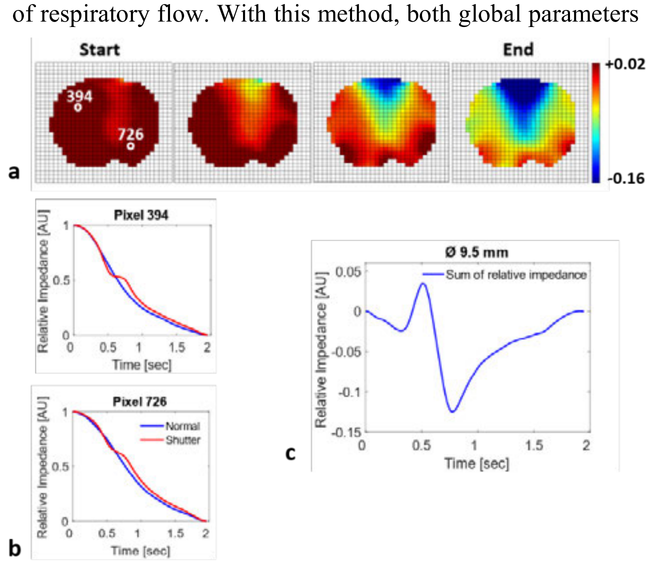

Figure 3: (a) Ventilation distribution within the difference images during the shutter maneuver (start, two selected time points in between and end of the shutter maneuver) for the airway resistance with Ø 9.5 mm for volunteer V3. (b) Relative impedance over time is shown for the two pixels 394 (ventral region) and 726 (dorsal region) (c) as well as the normalized sum of relative impedance of all pixels.

(e.g. airway resistance) and knowledge about regional ventilation can be obtained, which allows a better assessment of lung health.

4 Discussion

This first study shows that regional differences in ventilation distribution during normal breathing with short-term airway closures can be obtained using EIT. Different pulmonary pressures were induced by using various artificial airway resistances, resulting in differences in regional ventilation distribution. Patients with respiratory diseases have higher pulmonary pressures in comparison to healthy persons, so that this method might be useful for the detection of changes in regional ventilation. However, only measurements with healthy volunteers were carried out within this study. Airway obstructions were simulated, but this has probably no big influence on the healthy lung tissue of the volunteers. Since lung tissue of patient with real airway obstructions has reversible and irreversible changes, this might lead to different results. A higher pulmonary pressure due to the shutter could lead to the opening of previously closed lung areas, and therefore to a different ventilation distribution in comparison to our results. It is already known that regional lung function correlates with the severity of the patient's airway obstruction [5,6]. Our results indicate that it might be possible to confirm this correlation even with a normal breathing method and not only with forced breathing maneuvers. In future, EIT might be a useful tool in diagnosis of pulmonary diseases as well as in the follow-up even under normal breathing conditions.

5 Conclusion

This study demonstrates that regional differences in ventilation distribution can be detected with EIT during the performance of the ROcc method.

The use of artificial airway resistances (Ø 12.5 mm, Ø 10.5 mm and Ø 9.5 mm) induces higher pulmonary pressures in comparison without an additional airway resistance (Ø 30.0 mm). This could probably lead to the observed changes in regional ventilation. The obtained results should be confirmed with a higher number of subjects as well as in a follow-up study with patients with real airway obstructions. EIT in combination with the ROcc method could be a promising approach in pulmonary function monitoring in the future. Beneficial of this method would be that it is not exhausting and does not depend on the cooperation of the patient.

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Author Statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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