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Effect of the number of electrodes on the reconstructed lung shape in electrical impedance tomography

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Abstract: Electrical impedance tomography (EIT) is used to monitor the regional distribution of ventilation in a transversal plane of the thorax. In this manuscript we evaluate the impact of different quantities of electrodes used for current injection and voltage measurement on the reconstructed shape of the lungs. Results indicate that the shape of reconstructed impedance changes in the body depends on the number of electrodes. In this manuscript, we demonstrate that a higher number of electrodes do not necessarily increase the image quality. For the used stimulation pattern, utilizing neighboring electrodes for current injection and voltage measurement, we conclude that the shape of the lungs is best reconstructed if 16 electrodes are used.

Keywords: electrical impedance tomography; image quality.

1 Introduction

Electrical impedance tomography (EIT) is an emerging medical imaging technique, which is used in a clinical context to generate tomographic images of the thorax, depicting regional ventilation of the lungs. Currently, EIT is mainly used in the intensive care unit, where the regional information about lung ventilation is used to adjust ventilator parameters and thus prevent ventilator induced lung injuries [1]. Recently it has also been used in the examination of spontaneously breathing patients suffering from obstructive lung diseases such as chronic obstructive lung disease (COPD) [2], cystic fibrosis (CF) [3] or asthma.

In EIT an array of electrodes is attached around the circumference of the thorax. It is assumed that the impedance of the lungs increases during inspiration. Electrodes are used to inject small alternating currents and measure resulting voltages.

In clinical context difference-EIT is an established method to visualize changes in impedance, rather than absolute values of impedance. This modality is less sensitive to unknown electrode contact impedance and unknown thorax shape. A reconstruction algorithm is used to generate tomographic images of impedance variations from changes in measured electrode voltages. Usually one set of voltages is recorded at end-expiration, whereas another set of voltages is traced after inspiration. The underlying changes in impedance are reconstructed from the voltage measurements and displayed in real-time. Compared to structural images techniques, such as x-ray computed tomography (CT), the images of impedance change are severely blurred and structural information cannot be obtained. Thus, in many EIT applications only specific measures, e.g. the centre of ventilation (CoV) [4] or the global inhomogeneity index (GI) [5] are used.

However, the allocation of structural lung information (e.g. derived from CT) to functional images of the lungs (from EIT) is necessary for a comprehensive diagnosis. Therefore, EIT images should preserve the position and the shape of the lungs.

Typically the number of measured voltages is by orders of magnitude lower than the number of pixels depicting the reconstructed impedance changes. Thus, it seems obvious to increase the number of electrodes (and as a result the number of measured voltages) to increase image quality. The objective of this study is to compare different quantities of electrodes used for current injection and voltage measurement regarding their preservation of lung shape in reconstructed images.

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2 Methods

2.1 Simulation of voltages

Calculations have been carried out with MATLAB 2015a (Mathworks, Natick, MA) and the EIDORS toolbox [6]. Meshes of the used finite element models (FEM) were generated using NETGEN [7].

Usually the EIT problem, i.e. reconstructing internal changes in impedance (or conductivity) from voltage measurements on the surface is solved on a discretized domain. For voltage simulations we used 3D FEM models. The height of the models was set to 1.5, the semi major axis of the elliptical base area was set to 1, the semi minor axis to 0.8. Two elliptical cylinders with a semi minor axis of 0.5 and a semi major axis of 0.9 were placed inside the virtual phantom to simulate the lungs. The centre positions of the "lung cylinders" were set to −0.45 and 0.45 on the x-axis. Circular electrodes were attached equidistantly around the circumference at a height of 0.75. An exemplarily illustration of the FEM model with 32 electrodes is depicted in Figure 1.

The conductivity of FEM elements belonging to the "lung cylinders" was varied between $\sigma_{exp} = 74$ mS/m and $\sigma_{insp} = 43$ mS/m to simulate conductivity changes during breathing. Elements not belonging to the "lungs" were set to a constant value of $\sigma_{bkg} = 480$ mS/m. The number of electrodes was varied systematically in steps of four from n = 8 to n = 32. The "adjacent injection pattern" was used to simulate voltage vectors $\mathbf{v}_{exp}$ and $\mathbf{v}_{insp}$, where neighbouring electrodes are used for current injection or voltage measurement, respectively. Current injecting and measuring electrodes are changed in a rotating manner.

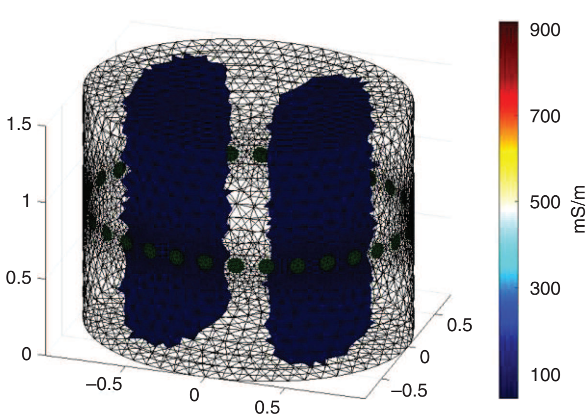

Figure 1: Simulation model with 32 circularly attached electrodes and elliptical cylinders to simulate the lungs.

Voltages are not measured on the electrodes used for current injection, such that $\mathbf{v} \in \mathbb{R}^{(n \cdot (n-3)) \times 1}$.

2.2 Image reconstruction

A one-step Gauss-Newton solver was used to reconstruct conductivity changes from simulated voltage changes.

$$\widehat{\mathbf{x}} = \mathbf{B}(\lambda) \cdot \mathbf{z} \tag{1}$$

where $\widehat{\mathbf{x}}$ is the vector of reconstructed conductivity changes and $\mathbf{z}$ contains normalized relative voltage changes such that $z_i = (v_{insp,i} - v_{exp,i}) / v_{exp,i}$, where i denotes the i-th component of the voltage vector. The reconstruction matrix $\mathbf{B}(\lambda)$ depends on the hyperparameter λ which controls the amount of regularization that is used to solve the ill-posed EIT problem. A detailed description of how to obtain the reconstruction matrix $\mathbf{B}(\lambda)$ can be found e.g. in [8]. To account for current propagation above and below the electrode plane a "dual-model 2.5D" reconstruction approach was used for image reconstruction [9].

To enable a comparison between reconstructed images with different quantities of electrodes, we chose the hyperparameter λ such that a noise amplification of 0.5, 0.75 or 1 was achieved. The noise amplification NF is defined to be

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{mean(|\mathbf{z}|)}{\sqrt{var(\mathbf{n})}} / \frac{mean(|\mathbf{Bz}|)}{\sqrt{var(\mathbf{Bn})}} \tag{2}$$

where $\mathbf{n}$ is a noisy signal of voltage changes and $\mathbf{Bn}$ is a reconstruction using the noisy voltage signal [10].

2.3 Evaluation of lung shape

To evaluate the shape of the reconstructed lungs we developed the shape mismatch measure (SMM) which is defined as

$$SMM = \frac{\sum (b_i \wedge p_i) - \sum (b_i \wedge \neg p_i)}{\sum p_i} = \frac{\hat{A}_{inside} - \hat{A}_{outside}}{A_{org}} \tag{3}$$

with

$$p_i = \begin{cases} 1 & , \textit{if FEM element belong to the lung} \\ 0 & , \textit{else} \end{cases}$$

$$b_i = \begin{cases} 1 & , \textit{if } \hat{x}_i < 0.3 \min(\widehat{\mathbf{x}}) \\ 0 & , \textit{else} \end{cases}$$

SMM values range from 1 to −1, where $SMM = 1$ indicates that the area of the reconstructed lung is equal to the area of the lung used in the simulation. Therefore, $\hat{A}_{inside} = A_{org}$. In this case $\hat{A}_{outside} = 0$, which can be considered as a perfect reconstruction of the lung shape. A value of $SMM = -1$ indicates that the reconstruction is not useful, since no parts of the reconstructed lungs coincide with the original lung. Since reconstruction artefacts at the boundary of the domain affect the *SMM* calculation, elements in the outer three rings of the FEM mesh were not considered.

3 Results

An exemplary illustration of reconstructed images of conductivity changes with different number of electrodes is depicted in Figure 2.

The more electrodes are used for voltage measurement, the more pronounced is the extension of the reconstructed lung shape in anterior-posterior direction (y-direction), whereas the reconstructions with only few electrodes leads to compressed lungs regarding the extension in this direction (see Figure 2). Additionally, the contours of the lungs are less blurred if more electrodes are used.

However, more electrodes do not necessarily improve the image quality, as measured with the above described *SMM* value. In all reconstructions the lowest *SMM* value was obtained for n = 8. Highest *SMM* values are obtained for n = 16. Figure 3 reveals that *SMM* values decrease if more than 16 electrodes are used for current injection and voltage measurement.

4 Discussion

In this paper, we demonstrated with a simulation study that the number of electrodes used for current injection and voltage measurement influences the shape of the reconstructed images of conductivity changes. Thereby more electrodes do not necessarily improve the image quality.

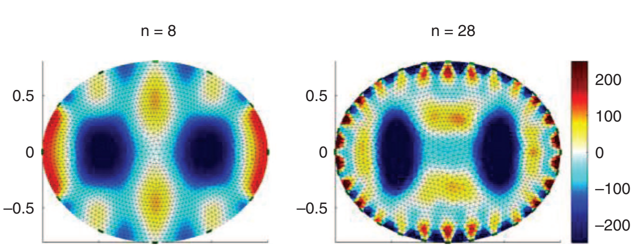

Figure 2: Reconstruction of lung shapes with different numbers of electrodes. Left: eight electrodes; Right: 28 electrodes.

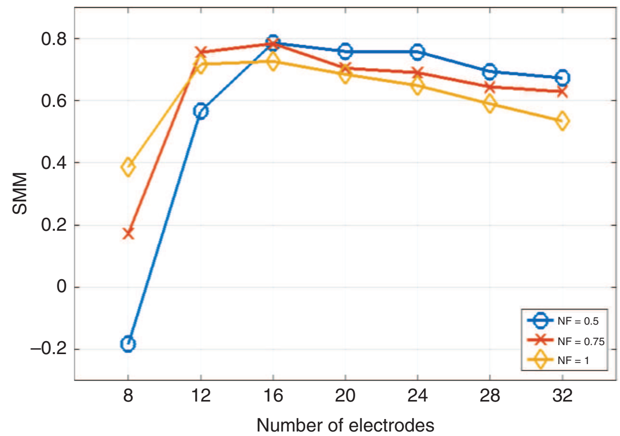

Figure 3: SMM values for different quantities of electrodes. Blue circle: NF = 0.5; Red X-marks: NF = 0.75; Yellow Diamond: NF = 1.

For the used model the reconstructions made with 16 electrodes best preserved the shape of the lungs.

In this simulation study we used the "adjacent stimulation pattern", which is the most often used pattern for current injection and voltage measurement. Several other patterns have been developed. The effect of the quantity of electrodes needs to be examined with other patterns in future work. Additionally, simulations were carried out on a simple ellipse shaped model and electrodes were spaced equidistantly. Further research should try to answer the question how many electrodes are necessary and where they should be placed to best depict the lung shapes of individual patients? Lung shapes might be obtained from CT data, which would lead to a patient specific EIT configuration, where quantity and placement of electrodes are determined individually. This could enable an easier correlation and allocation of anomalies in the EIT images with morphological imaging techniques and thus improve the interpretability of EIT images.

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