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Improving image quality in EIT imaging by measurement of thorax excursion

Abstract: Electrical Impedance Tomography (EIT) is used to visualize the regional ventilation of the lungs using voltage measurements on the surface of the thorax. Unfortunately the image reconstruction process is sensitive to shape deformation. During breathing the inevitable expansion of the thorax influences measured boundary voltages which leads to artifacts in the reconstructed images. A camera based motion-tracking-system was used to measure thorax excursion during breathing and systematically modify measured voltages. Results indicate that image artefacts can be reduced if the measured voltages are modified based on the measured thorax excursion.

Keywords: Electrical Impedance Tomography; Medical Imaging; Thorax Excursion

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1 Introduction

Electrical Impedance Tomography (EIT) is an imaging modality used to visualize the regional ventilation of the lungs in ventilation therapy. Therefore electrodes are attached around the circumference of the thorax. Small alternating currents are injected into the body and resulting voltages are measured. During inspiration the lungs are filled with air and the alveoli expand. This leads to constricted but lengthened current paths and therefore affects the voltages on the boundary of the thorax [1]. Measured voltage changes are used to reconstruct an image of the internal conductivity change and thus the regional ventilation of the lungs. This technique is non-invasive, radiation-free and relatively inexpensive, making it suitable for long-term bedside monitoring of lung aeration [2]. EIT is promising to guide ventilation therapy and reduce the risk of ventilator induced lung injury (VILI) [3].

Besides the internal change in conductivity, boundary voltages are also affected by the inevitable expansion of the thorax during breathing [4, 5]. The traditional approach for image reconstruction does not consider voltage change caused by domain deformation which results in artefacts in the reconstructed images.

In this article we describe a method to integrate knowledge of thorax deformation into the reconstruction process. Results demonstrate that this method improves image quality in EIT imaging.

2 Methods

2.1 General

A commercially available EIT system (PulmoVista500, Draeger Medical, Luebeck, Germany) was used to measure boundary voltages at the thorax of a volunteer (healthy, 32 years, male). A belt with 16 electrodes was attached at the 5^{th} intercostal space. The subject performed maximum expiration followed by maximum inspiration in sitting position.

Every electrode was equipped with a reflective marker. During the breathing manoeuvre the position of every marker was determined with a camera based motion-tracking-system (Bonita, VICON, Denver, CO) consisting of 9 infrared cameras. In this article we only consider 2D EIT. We therefore projected the three dimensional electrode coordinates onto a regression plane obtained using a least squares approach. These two dimensional positions were used to modify measured voltages.

We used NETGEN [6] to generate FEM meshes to simulate the influence of shape deformation on the boundary voltages. FEM meshes of the deformed thorax were obtained with two methods.

1. Precise mesh: Generate mesh using the actual position of the electrodes for every change in thorax shape.
2. Simplified mesh: Generate mesh at maximum expiration. Stretch this mesh by shifting of the nodes according to the anterior-posterior and lateral deformation of the thorax.

The first method results in meshes that more precisely represent the current thorax geometry compared to the second method, with the drawback of time consuming remeshing for every change in geometry. The second method

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uses an initial geometry which is stretched based on the deformation in two directions (Figure 1). For the used FEM mesh (11138 elements) the shifting of the nodes can be calculated in real time, but more complex deformations are not incorporated in this model.

For the considered breathing manoeuvre we generated 20 FEM meshes for each method and 20 EIT frames were used to visualize the ventilation change.

2.2 Modification of boundary voltages

A common pattern for current injection and measurement is to use adjacent electrodes. For the used EIT system this leads to 208 voltages v_{frame} for every frame. An established method for image reconstruction calculates the change in conductivity from the measured voltages v_{frame} with a one-step Gauss-Newton solver, which leads to

$$x = B \cdot f(v_{frame}) \tag{1}$$

where B is the reconstruction Matrix that relates the measured voltages to a vector x of conductivity change [7]. This method is hereinafter referred as traditional approach.

We used the FEM model to simulate the ratio η of measured voltages difference, based on the deformation of a homogeneous model with uniform conductivity. We express the ratio

$$\eta_i = \frac{v_{org,i} - v_{def,i}}{v_{def,i}} \tag{2}$$

with $v_{org,i}$ being the simulated i-th component of the voltage on the thorax at maximum expiration (reference thorax shape) and $v_{def,i}$ the respective component of the deformed domain.

We calculated η for every FEM mesh, which leads to the following matrix

$$H_{20\times208} = [\eta_1 \ldots \eta_{20}]^{\mathbf{T}} \tag{3}$$

with η_n being the voltage ratio between the n-th frame and the reference thorax shape.

For each frame the voltages used for image reconstruction are subsequently modified according to

$$v_{corr,i} = H_{frame,i} \cdot v_{frame,i} + v_{frame,i} \tag{4}$$

with v_{corr} containing the modified voltages used for image reconstruction and $v_{frame,i}$ being the i-th component of the measured voltage at the considered frame.

2.3 Artefact amplitude measure

To evaluate the effect of the modification of boundary voltages we use the common method of Artefact Amplitude Measure (AAM) which is:

$$AAM = \sqrt{\frac{\Sigma_{i\in L}\Omega_i x_i^2}{\Sigma_{i\in L}\Omega_i}} \tag{5}$$

where x_i is the change in conductivity of the FEM element i and Ω_i is the area of the same element [8]. The subset of elements used for calculation of AAM is denoted L. We define L to contain the outer elements of the FEM, as excursion induced artefacts mainly occur at this region [9].

3 Results

3.1 Thorax deformation and mesh generation

The dominating deformation during the breathing manoeuvre is in anterior-posterior direction which is approximately 4 times the deformation in lateral direction.

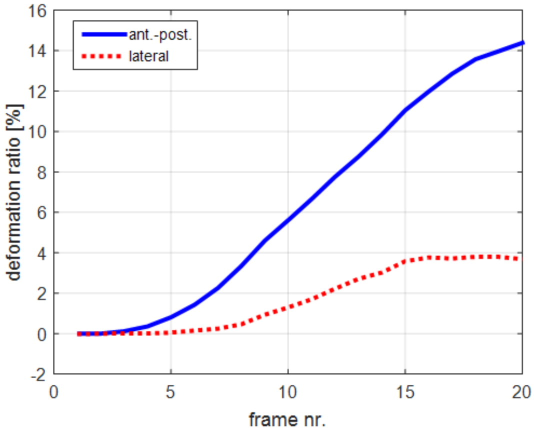

Figure 1: Deformation ratio during maximum inspiration in anterior-posterior direction (solid blue line) and in lateral direction (dotted red line).

The positions of the boundary nodes of the FEM meshes generated with the above described methods are depicted in Figure 2.

Both geometries show the shape at maximum inspiration. Especially the deformation of the ventral chest differs when the mesh is stretched (simplified mesh) compared to the more accurate method (precise mesh) where a new mesh is generated for every frame.

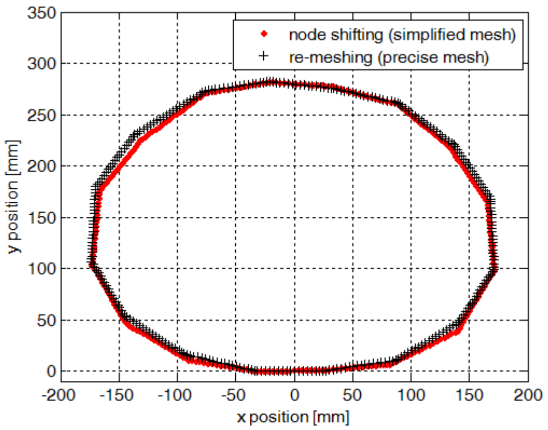

Figure 2: Outer geometry of the FEM mesh generated with re-meshing for every change in thorax excursion (black plus) and for the stretched mesh based on the deformation in two dimensions (red dot).

3.2 Image reconstruction

Images were reconstructed with the traditional approach using the measured voltages and with the above described methods where obtained voltages are modified based on simulations on homogeneous FEM models.

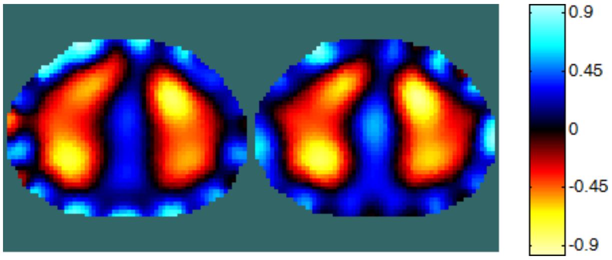

Figure 3: Reconstructed conductivity of frame 16. Left: Reconstruction with traditional approach. Right: Approach using modified boundary voltage based on precise FEM mesh. Red colour indicates decreasing conductivity.

Results indicate that for every considered frame, the amount of boundary artefacts is reduced when the precise FEM mesh is used to calculate the modification of boundary voltages used for image reconstruction according to Eq. 4 and Eq. 1. Figure 3 shows the reconstructed conductivities of frame 16.

If the simplified mesh is used to modify the boundary voltages the amount of artefacts is reduced if thorax deformations are small, at higher deformations more boundary artefacts arise (Figure 4). Please note that the colouring is different for every frame to ensure that details in reconstructed conductivity can be identified more easily.

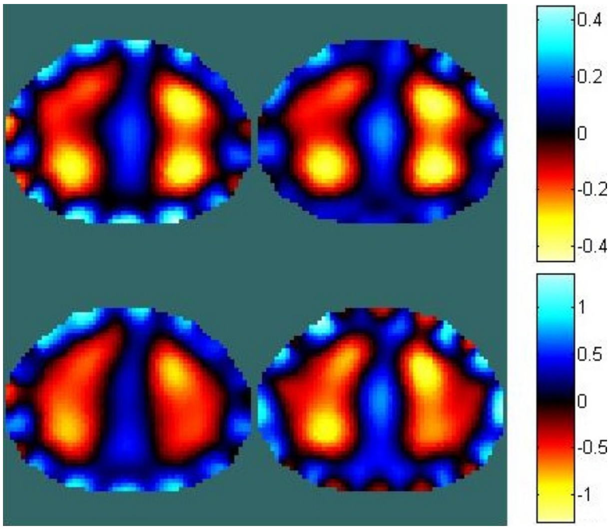

Figure 4: Upper row: Reconstructed conductivities at frame 8. Lower row: Reconstructed conductivities at frame 20. Left column: Reconstruction with traditional approach. Right column: Reconstruction with modified voltages based on stretched FEM model (simplified mesh).

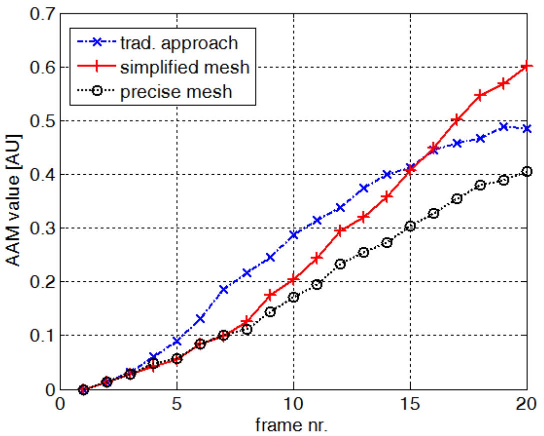

Figure 5: AAM values of the different reconstruction methods. Traditional approach (x marker), modification of voltages using simplified mesh (plus marker), modification of voltages using precise mesh (circle marker).

Figure 5 shows how the amount of boundary artefacts depends on the reconstruction method for all considered frames. For small deformations until frame 7 both introduced approaches show nearly the same AAM values. Both methods using modified voltages outperform the traditional approach until frame 15. For very high thorax deformations the simplified mesh results in more boundary artefacts compared to the traditional approach while the method that uses the mesh using all electrode positions increases image quality even for very high deformations.

4 Discussion

Results demonstrate how knowledge of thorax excursion can be used to increase image quality in EIT imaging. The approach using the precise FEM mesh to modify measured voltages performs better than the traditional approach, however it has to be mentioned that such sophisticated systems for measuring the thorax excursion are usually not available in a clinical context. A relatively naďve method, where the thorax geometry is stretched based on anterior-posterior and lateral deformation, can result in lower boundary artefacts if the excursion of the thorax is relatively small. We hypothesize that the mismatch of the simplified mesh to the original body geometry (Figure 2) results in increased AAM values for higher thorax excursions (Figure 5). It has to be investigated how thorax excursion can be approximated more exactly by using only sparse information of deformation. This would help to develop a system that uses the described approach and which might be suitable for clinical applications. Thus knowledge of the boundary deformation will lead to more detailed reconstructed images with less artefacts. This improves image interpretation and helps EIT to become a more commonly used imaging technique for lung monitoring.

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

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