Modelling of the electric potential distribution in a thorax phantom for Electrical Impedance Tomography using the Finite Element Method

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Abstract

Electrical impedance tomography (EIT) is a non-invasive technique for the estimation with a high temporal resolution of the spatial impedance distribution in a cross section of the body. Electrodes are attached around the domain of interest (e.g. the thorax). Small alternating currents are injected and potentials are measured and used for reconstruction. The reconstructed impedance images can be particularly useful for the treatment of patients with acute respiratory distress syndrome (ARDS). This severe disease is characterised by atelectases and lung oedema and, thus, changes of the impedance distribution in the thorax. An electrolytic thorax phantom is used for the analysis of different pathology states. It contains simple functional units that mechanically simulate heart and lung. In order to increase flexibility regarding the positioning of the electrodes, the simulation of the pathology, the positions of the organs and tissue properties, a parameterised adjustable 2D-model has been developed. The potential and current distributions are computed using the finite element method (FEM). The obtained images show the potential for automatic closed-loop parameterisation and reconstruction algorithm evaluation.

Introduction

Thoracic electrical impedance tomography (EIT) is a method that aims at reconstructing images of internal electrical property distributions (usually conductivity and permittivity) in human or animal subjects [1-2]. *N* electrodes are equidistantly attached to the skin around the subject's thorax. All adjacent electrodes are sequentially supplied with small sinusoidal currents (e.g. 5 mA_{rms}, 50 kHz) using a digital-to-analog converter (DAC), while the transfer voltages at the (*N*-3) remaining electrode pairs are measured with an analog-to-digital converter (ADC), see fig. 1.

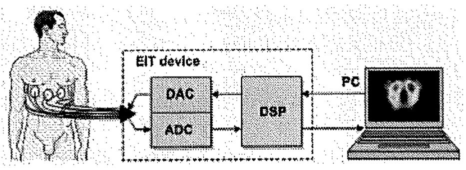

Figure 1. Principle of EIT measurements around the thorax (DSP = Digital Signal Processor).

As governed by Poisson's equation, the resulting voltages are a function of not only the applied current distribution, but also the internal and boundary impedance distribution and the geometrical shape of the subject. This makes the image reconstruction an ill-posed and nonlinear problem [3].

The reconstructed impedance images provide valuable information for the refinement of several clinical treatments such as artificial lung ventilation, cardiac volume changes, gastric emptying and head imaging [2]. EIT seems to be particularly useful for bedside monitoring of patients with acute respiratory distress syndrome (ARDS). This life-threatening disease of the lung is characterised by pulmonary inflammations, which finally lead to alveolar lung oedema (water in the lung) and atelectases (collapsed parts of the lung) and, thus, changes of the impedance distribution. State-of-the-art medical treatment includes artificial ventilation with special ventilation schemes that can be monitored in real-time by EIT [4].

2 Phantom and Model

For the development of EIT hardware and the validation of reconstruction algorithms, EIT phantoms are widely used [5]. We added functional units to an existing electrolytic phantom in order to mechanically simulate lung and heart, see fig. 2 and 3.

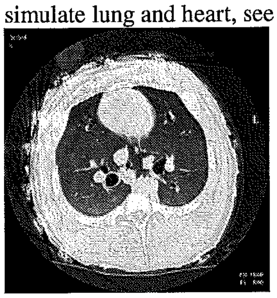

Figure 2. Thoracic CT scan of a pig directly in the electrode plane (dark area = lung, white "blob" = heart).

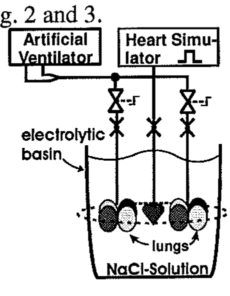

Figure 3. Electrolytic thorax phantom (electrode plane symbolised by the dashed line).

In order to increase the flexibility of the experimental set-up regarding the positioning of the electrodes, the simulation of the pathology, the position of the organs and tissue properties, a finite element model of the phantom, or even of a porcine or a human subject, would be advantageous. Even more beneficial would be a fully automatic simulation cycle. This can be achieved if the geometric model is described by a small set of parameters. Hence, a parameterised 2D-model of the thorax phantom has been developed, which is controlled by MATLAB® and meshed with ANSYS®.

The resulting mesh is transmitted to the iMOOSE package [6], which provides the finite element solver as well as visualisation and post-processing facilities. Re-entering the simulation results into MATLAB® allows then a closed-loop parameter refinement and the application of different nonlinear solver approaches to the inverse problem.

3 Field simulation

The forward EIT problem is simulated using the Finite Element Method (FEM). The formulation uses the electric vector potential V as unknown. In Galerkin form, it reads:

$$\int_\Omega (\sigma + j\omega\varepsilon)\,\mathrm{grad}\,\alpha_i \cdot \mathrm{grad}\,V\,\mathrm{d}\Omega =$$

$$\int_\Gamma \alpha_i \cdot J_n\,\mathrm{d}\Gamma \quad \forall i = 1\ldots n_n$$

where σ is the electric conductivity, ω the angular frequency and ε the electric permittivity; the α_i's are the weighting functions for n_n nodes. The current impressed through the electrodes (current density J_n) is introduced by a Neumann boundary condition. Material properties are obtained from [7], ranging between 0.025 S/m (fat) to 0.26 S/m (deflated lung) for the conductivity and relative permittivities in the range between 200 (fat) and more than 15,000 (heart).

Fig. 4 shows the real part of the potential distribution and current density ($\vec{J} = -(\sigma + j\omega\varepsilon)\mathrm{grad}\,V$) when a current flows inwards through one electrode, and outwards through the neighbouring one. Fig. 5 shows the equivalent for the imaginary component. It can be noted, that due to the large value of the relative permittivity in the heart, the imaginary part of the current flow is relatively large compared to the rest of the model.

4 Conclusion

The thoracic EIT is a computationally challenging subject, combining FEM techniques for the forward solution of the problem and nonlinear inverse problem solvers. A thorax phantom allows the comparison of the simulations with measurements, and a parameterised geometric 2D-model constitutes the basis for a fully automatic simulation cycle. Further results will be presented in the full paper.

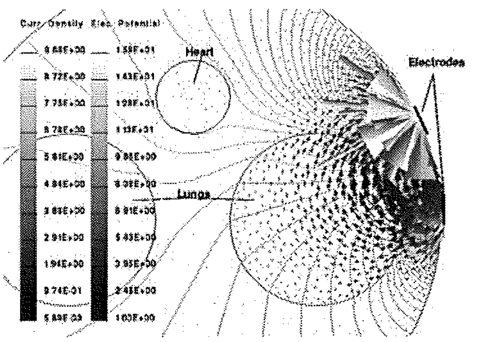

Figure 4. Potential and current density (real component).

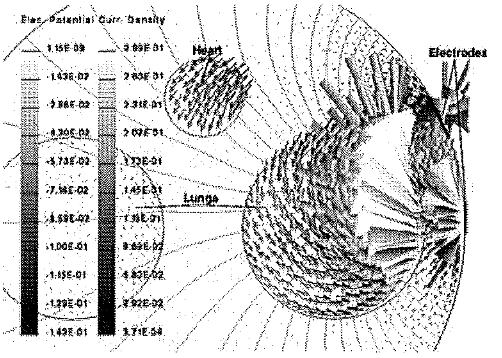

Figure 5. Potential and current density (imaginary component).

5 Literature

[1] D. C. Barber, B. H. Brown, and I. L. Freeston, "Imaging and spatial distributions of resistivity using applied potential tomography", Electronics letters, vol. 19, pp. 93-95, 1983

[2] H. Dehghani, N. Soni, R. Halter, A. Hartov, K. D. Paulsen, "Excitation patterns in three-dimensional electrical impedance tomography", Physiological Measurement, vol. 26, pp. 185-197, 2005

[3] P. Hua, E. J. Woo, J. G. Webster, W. J. Tompkins, "Finite Element Modeling of Electrode–Skin Contact Impedance in Electrical Impedance Tomography", IEEE Transactions on Biomedical Engineering, Vol. 40, No. 4, pp. 335-343, April 1993

[4] J. A. Victorino, J. B. Borges, V. N. Okamoto et al, "Imbalances in regional lung ventilation: a validation study on electrical impedance tomography", Am J Respir Crit Care Med., vol. 169, no. 7, pp. 791-800, 2004

[5] H. Griffiths, "A phantom for electrical impedance tomography", Clin. Phys. Physiol. Meas., vol. 9, pp. 15-20, 1988

[6] G. Arians, T. Bauer, C. Kaehler, W. Mai, C. Monzel, D. van Riesen, and C. Schlensok, "Innovative modern object-oriented solving environment - iMOOSE", http://www.imoose.de, [Online].

[7] S. Gabriel, R. W. Lau, C. Gabriel, "The dielectric properties of biological tissues: II. Measurements in the frequency range of 10 Hz to 20 GHz", Phys Med Biol., vol. 41, no. 11, pp. 2251-2269, 1996