

Image-based Simulation of Electrical Impedance Techniques Applied on the Human Thorax for Cardio-pulmonary Applications

F. K. Hermans¹, R. M. Heethaar¹, R. T. Cotton², and A. Harkara^{*2}

¹VU University Medical Center, ²Simpleware Ltd.

*Corresponding author: Rennes Drive, Exeter, EX4 4RN, UK, a.harkara@simpleware.com

Abstract: For medical diagnostic purposes there is an increasing need for non- (or minimal) invasive techniques to measure all kinds of parameters that can provide insight in the functioning of cells, organs or organ systems. For instance, for many years researchers are looking for non-invasive methods that give information about the amount of blood that is ejected by each cardiac contraction (stroke volume) and methods that inform us about the functioning of the lungs during normal breathing or artificial ventilation. Currently, Impedance Cardiography (ICG) is used for measurements of the heart and Electric Impedance Tomography (EIT) is used for investigating lung tissue condition. This paper focuses on calculating the current distributions for these two techniques in models of the human thorax. These calculations give a profound insight what can be expected from these techniques.

Keywords: Image, mesh, cardio-pulmonary, electrical, conductivity

1. Introduction

To measure stroke volume, methods are being developed in which a small, harmless alternating current is injected into a patient. The current distributes through the thorax, dependent of the intra-thoracic impedances of the tissues. Resulting voltages are measured with additional electrodes on the thorax. If the heart contracts, the diameter of the aorta increases. Its electrical impedance changes as well and changes in voltages at the skin occur. From the heart synchronous variations in voltages estimates are made of function parameters of the heart, like stroke volume. This technique is called Impedance Cardiography (ICG) [1, 2].

To measure the filling of the lungs with air, comparable methods are being developed. In this situation a ring of (mostly 16) electrodes is attached to the patients thoracic skin in a plane perpendicular to the length axis of the patient. Two neighbouring electrodes inject a small

alternating current; resulting voltages are measured at all other 13 adjacent electrode pairs. Then two other neighbouring electrodes are used for injection of the current and again voltages are measured at all other electrode pairs. This procedure is repeated until injection has been done around the full circle and 208 (13*16) voltage measurements are carried out. From these measurements one tries to reconstruct the impedance distribution in the electrode plane. As lungs, muscles, blood etc. have different impedances the reconstructions provide information about the lung condition in the cross-section of the patient. In this way the air ventilation and blood circulation through the lungs can be investigated. This procedure is called: Electric Impedance Tomography (EIT) [3, 4]

2. Methods

Difficulties in creating 3D geometries from 2D images are widespread in biomedical engineering and research. 3D geometries are not only essential for finite element analysis, but also necessary for implant creation or high precision brain surgery.

The Simpleware software package consists of two programs; ScanIP and ⁺ScanFE. ScanIP was used to import the DICOM files and to segment the regions of interest. Then the image is segmented by the user. This can partially be performed by using a set of threshold segmenting tools. The resulting segmentation can be optimized by a wide range of filters to smooth the segments or to fill tiny holes. ScanIP then creates a 3D geometry by forming voxels with the length of two sides defined by the pixel size of the MR image and the third length defined by the sum of the slice thickness and the slice gap.

The geometry is smoothed and exported to ⁺ScanFE. ⁺ScanFE generates the finite element mesh by creating a mesh with tetrahedral elements from the voxels [5] as can be seen in Figure 1. In this way the mesh consisted of

typically 350,000 elements and was exported directly to COMSOL.

Models were based on a healthy 25 year old male subject. MRI images were triggered at end-inspiratory and end-expiratory state combined with end-systolic and end-diastolic state. In this way four geometries were constructed.

In order to be able to apply electrical current conditions at the right places, electrodes are drawn in the segmentation process. Figure 2 shows the segmented regions of the heart and lungs used for mesh generation.

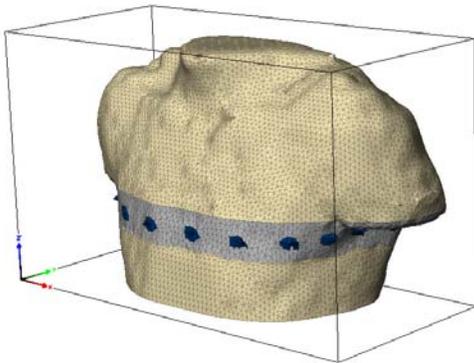


Figure 1. Mesh generation in *ScanFE for the Electrical Impedance Tomography study

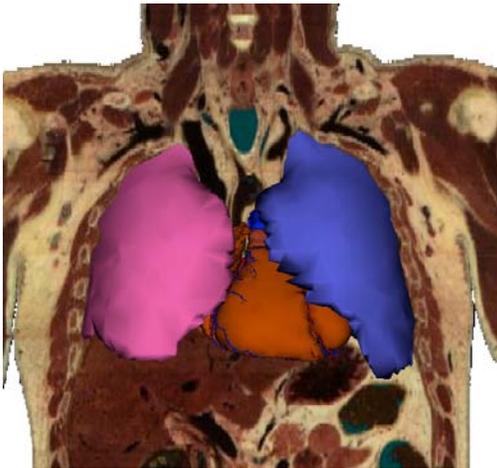


Figure 2. Segmented regions of interest for the Impedance Cardiology study

3. Use of COMSOL Multiphysics

The resulting finite element mesh was then exported to COMSOL where the point settings,

boundary conditions, and sub-domain settings for the partial differential equation (PDE) were set. The PDE is set up starting with the point form of Ohm's law. This PDE is solved by the Comsol Conductive Media DC module. Alternating current within the frequency range of 50 – 100 kHz as used in impedance cardiography is assumed to be distributed on a macroscopic scale like direct current. Point settings are used to inject electrical current into the geometry. The electrodes painted in Simpleware appear as small sub-domains in Comsol. The electrode sub-domains only function as details in the geometry which enable the user to apply electrical currents. The electrode sub-domain of the electrodes therefore is deactivated in the finite element model. The points of the electrode sub-domain remain to set as current inflow points in the neck with the value of +5 mA and -5 mA at the thorax.

The outer boundary of the geometry, the skin of the subject, is set to insulation. The internal boundaries are set to 'continuity', which means that there are no internal boundary conditions. The sub-domain settings are the values for electrical conductivities, isotropic or different in each direction as given in Table 1.

Table 1: Conductivities of human tissues used in this research [6]

Tissue	Conductivity [S/m]
Muscle longitudinal	0.2
Muscle transversal	0.04
Blood	0.5
Heart muscle	0.22
Lung	0.08

4. Results

4.1 Impedance Cardiography

Figures 3 and 4 shows the visualization of the impedance cardiography solution of the volunteer, in end-diastolic expiratory state, using a four and two current electrode configuration. To visualize the current distribution through the thorax in an impedance cardiography

measurement, streamline plots are used. The color of streamlines is logarithmically related to the local current density. The organs are given a uniform color to accentuate the streamlines pointing in - and outwards the organs.

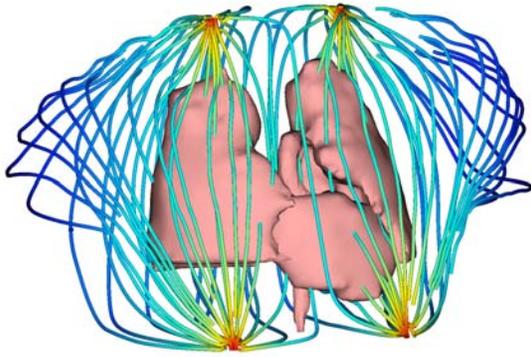


Figure 3. FEM solution of the four current electrode setup

One can clearly see that the electrical current streamlines are quite widely distributed through the thorax. Figure 2 shows that streamlines are flowing parallel to the aorta in a four electrode configuration, as opposed to Figure 3 where streamlines are crossing the aorta in a two electrode configuration.

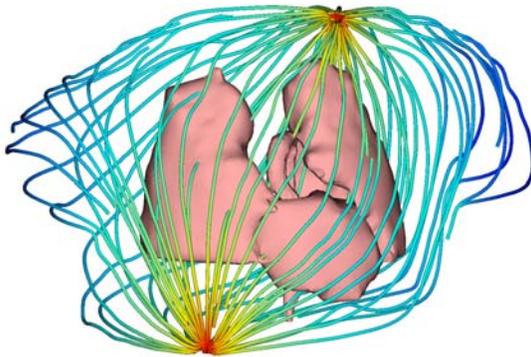


Figure 4. FEM solution of the two current electrode setup

4.1 Electrical Impedance Tomography

Figure 5 shows the solution of an electrical impedance tomography simulation based on the expiratory, end-diastolic dataset. As can be seen after comparison with Figure 43, electrodes 1

and 2 are used for electrical current injection. The current spreads widely over the geometry.

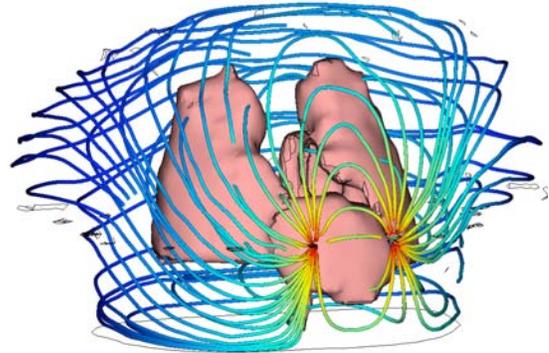


Figure 5. FEM solution of an EIT experiment, expiratory state, current electrodes no. 1 and 2

5. Discussion

5.1 Impedance Cardiography

The visualizations of the solution as depicted in Figure 2 and 3 show that the greater part of the electrical current density is not concentrated in the aorta, as stated by commercial ICG device producers, but widely distributed throughout the thorax. Because of the geometry of the human thorax, comparing the impedance contribution of different organs by determining the current through a plane is not the best manner since this always leads to over or under estimation of current distribution through different organs. Integration of electrical current over the volume of different organs is a better way to compare impedance contributions since the whole geometrical effect is taken into account, including the volume of organs.

Although integration of electrical current over the volume of organs is the best way to determine the relative influence of the different organs on the impedance signal, there are some disadvantages. The current percentage is dependent on the size of the model's geometry. Therefore this figure is only applicable to compare current contribution between organs in the same thorax. Neither the current integrated over volume nor the current contribution percentage is suited to predict the absolute value of impedance change due to the cardiac cycle in the impedance signal. A way to predict the

impedance change using the model would provide the opportunity to validate the model with experiments.

5.1 Electrical Impedance Tomography

The developed FEM models deliver interesting insight in the electrical current distribution throughout the upper thorax which is not possible to gain in a physical experiment. To validate the computational model, voltage differences between electrodes should be compared with real EIT measurements.

Although 2D experiments showed that the influence of ribs did not alter the current distribution through the organs significantly, the model would be more realistic when the bone structure could be taken into account to explore the 3D situation. The time a subject can hold his breath limited the scanning time and therefore the slice distance and caudocranial resolution.

With a higher caudocranial resolution, ribs could be segmented which would not only make the model realistic, but it would also be possible to optimize the ideal height at the thorax to place the electrodes to obtain the highest current percentage through the lungs and therefore the highest signal-to-noise ratio.

6. Conclusions

The finite element method is a well proved computational technique to investigate physical phenomena where an analytical approach is not possible. It showed already lots of applications in biomedical research and engineering.

Since the geometry is the starting point in a finite element simulation, the meshing algorithm is very important. In the biomedical field, geometries are generally curved which demands much from the meshing kernel.

The combination of a MRI dataset in inspiratory and expiratory breathing phase, the segmentation software and the finite element software enabled us to create a framework in which a wide variety of electrical impedance techniques can be modelled. It gave us an interesting insight in the current distribution through the human body in impedance cardiography and electrical impedance tomography measurements and offered interesting challenges for future research.

7. References

1. W G Kubicek, J N Karnegis, R P Patterson, D A Witsoe, R H Mattson, Development and evaluation of an impedance cardiac output system, *Aerospace medicine*, **37(12)**, 1208-12 (1967).
2. H. H. Woltjer, H. J. Bogaard and P. M. J. M. de Vries, The technique of impedance cardiography, *European Heart Journal*, **18**, 1396-1403 (1997).
3. J. Victorino et al., Imbalances in regional lung ventilation: a validation study on electrical impedance tomography, *American Journal of Respiratory and Critical Care Medicine*, **169**, 791-800 (2004).
4. C. Putensen, J. Zinserling, H. Wrigge, Electrical impedance tomography for monitoring of regional ventilation in critically ill patients, *Yearbook of Intensive Care and Emergency Medicine*, (2006).
5. P. Young et al, An efficient approach to converting 3D image data into highly accurate computational models. *Philosophical Transactions of the Royal Society A*, **366**, 3155-3173 (2008).
6. J. Wtorek, Relations Between Components of Impedance Cardiogram Analyzed by Means of Finite Element Model and Sensitivity Theorem, *Annals of Biomedical Engineering*, **28**, 1352-1361 (2000).

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