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Electromagnetic Field in Biological Tissue Objects

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Abstract: In this paper a method for automatic 3D model building is presented. These models are suitable for investigations of electromagnetic field distribution with Finite Element Method (FEM). Models are made by meshed structures and specific electromagnetic material properties for each tissue type. Mesh is built according to specific FEM criteria for achieving good solution accuracy. Bioimpedance measurement system is developed and electromagnetic properties, acquired by the system, are used in 3D FEM model. Achieved models are applied for electromagnetic field distribution investigation.

Keywords: 3D vector graphic, bioimpedance, measurement system, electromagnetic properties, electromagnetic field modeling, finite element method, biomagnetics.

1 Introduction

ELECTROMAGNETIC field distributions in biological objects are extremely important problem in experimental and theoretic aspect [1–13]. New generation of diagnostic medical equipment can acquire rich visual data sets. This information must be processed for visualization purposes and also can be very useful for solving of forward and inverse problems considering medical diagnosis and therapy [1–5].

Building quality vector models suitable for magnetic field calculations is a serious engineering problem.

In this paper we develop a method for automatic dynamic 3D model building. Models are made by time sequence of mesh structures and specific electromagnetic material properties for each tissue type. These models are suitable for investigations of electromagnetic field distribution using FEM. Mesh is built according to specific FEM criteria for achieving good solution accuracy. Also a measurement system for

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electromagnetic field property determination is proposed. Achieved 3D models are used for determination of electromagnetic field distribution in a human thorax.

2 Method Structure

Method structure is shown in Fig.1. Object information is processes in two stages - first, for the geometry data and second, for electromagnetic material properties.

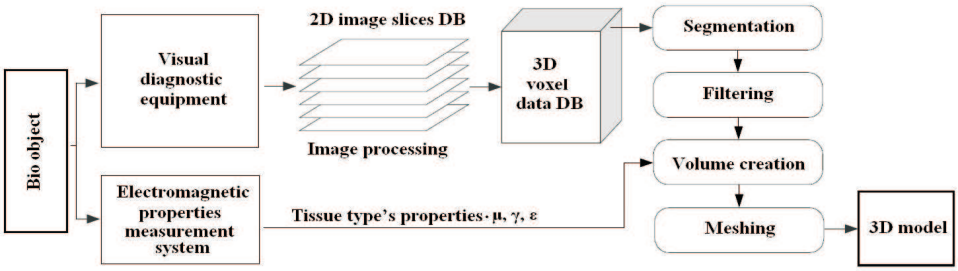


Fig. 1. Slices stack.

As input a sequence of 2D slices acquired by visual diagnostic equipment (ultrasound, CT or MRI) can be used. Image processing techniques may be used in that method stage for enhancement of image properties.

Acquired slices are collected in a 3D image stack. This stack is used for 3D voxel Data Base (DB) creation. All method manipulations are over that 3D voxel DB.

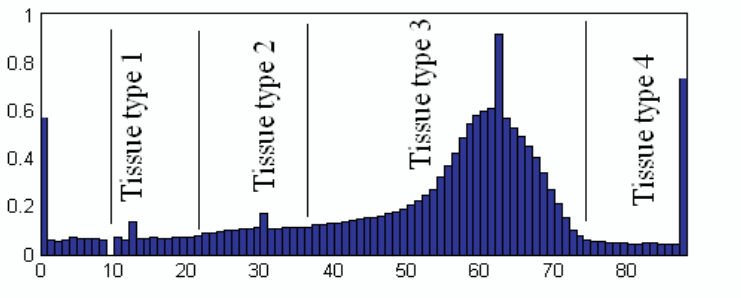


Fig. 2. Used for decomposition histogram.

Segmentation of anatomical organs has to be made semiautomatic by recognizing their contours in the 3D voxel DB. Tissue segmentation is made by voxel intensity histogram shown in Fig.2. Each tissue type is associated by its intensity level depending of used diagnostic equipment. Segmentation filtering procedure

is applied for tissue separation, shown in Fig. 3, where uncommon voxels are accepted from anatomical organ database.

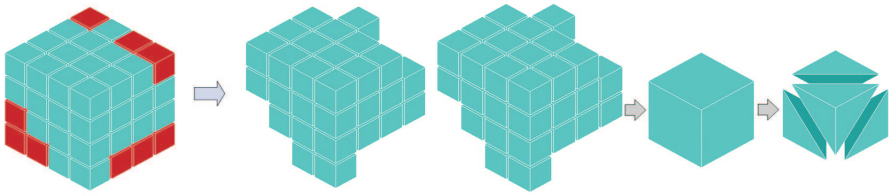


Fig. 3. Slices stack filtration.

Fig. 4. Voxels decomposition process.

Each voxel is decomposed in five tetrahedrons. For volume creation this tetrahedrons are glued together. Outer tetrahedrons could be deleted for smooth model surface.

Built volumes are associated with corresponding electromagnetic material properties. The model is imported in FEA software where can be meshed as volume object.

Electromagnetic properties as electric permittivity - ε, magnetic permeability - μ and electric conductivity - σ are acquired by bioimpedance measurement system.

3 Model Building

3D model of a part of a cardiac muscle is built for demonstration of capabilities of the method. The sequence of 2D slices is acquired by ultrasound scanner.

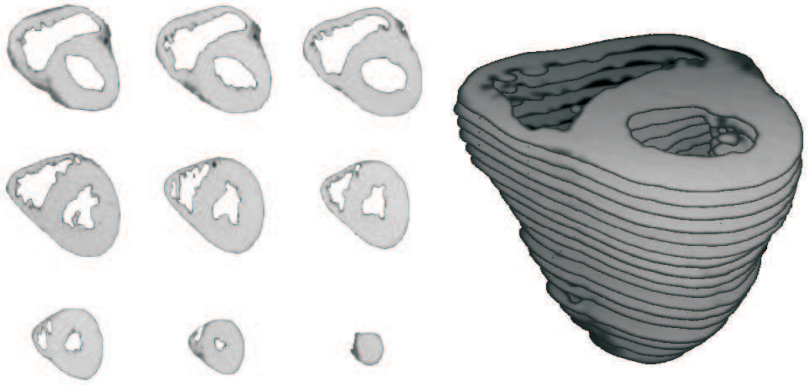
Image segmentation is made semi-automatic, where the heart muscle position and outer boundaries are pointed. Heart tissue filtered by its image intensity. It is used 22 slices stack. Distance between slices is 5mm. Some of used slices are shown in Fig.5(a). Slices, arranged in 3D, are shown in Fig.5-(b).

Software toolbox employing the proposed method is built as Matlab toolbox with its graphical interface. The developed toolbox allows a semiautomatic image sequence import and uses the Matlab function capabilities for image processing.

The toolbox supports a library with meshing algorithms that can be easily controlled or even combined. Also, the toolbox supports first and second order elements. Mesh building could be controlled according to specific FEM criteria for achieving good solution accuracy.

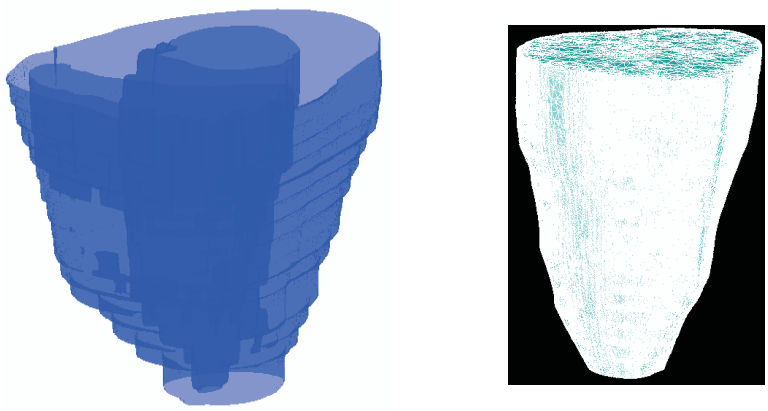
The 3D models can be exported as ANSYS-file format or as meshed solid structure list.

Slices are collected in 3D volume, as shown in Fig.6(a). The achieved list of elements is imported in ANSYS, shown in Fig.6(b).



(a) (b)

Fig. 5. Slices stack assembly.



(a) (b)

Fig. 6. Reconstructed volume.

Tissue electromagnetic material properties are applied for every element in the list.

4 Bioimpedance Measurement System

Experimental computer system is design for electromagnetic property measurements of biological objects. The proposed system is multi frequency bioimpedance measurement system. It employs Agilent 4294A precision impedance analyzer to measure the amplitude and the phase of a signal applied over a tested biological tissue sample. All frequency range from 40Hz to 110MHz is covered by the impedance analyzer. Also different measurement test-fixtures are included in mea-

surement system design. Measured data can be used for tissue characterization in width frequency range. The developed experimental computer system can interface with output devices acquiring flexible testing process.

5 Measurement Method

The auto balancing bridge method is used in measurement method [6–13]. For interconnecting an object under the test to the measurement terminals of the auto balancing bridge instrument, the four-terminal pair configuration is used. It can reduce the effects of lead impedances because the signal current path and the voltage sensing cables are independent (Fig. 7). The four-terminal pair (4TP) configuration solves the mutual coupling problem because it uses coaxial cable to isolate the voltage sensing cables from the signal current path. Since the return current flows through the outer conductor of the coaxial cable, the magnetic flux generated by the inner conductor is canceled by that of the outer conductor (shield). The measurement range for this configuration is improved to below 1Ω.

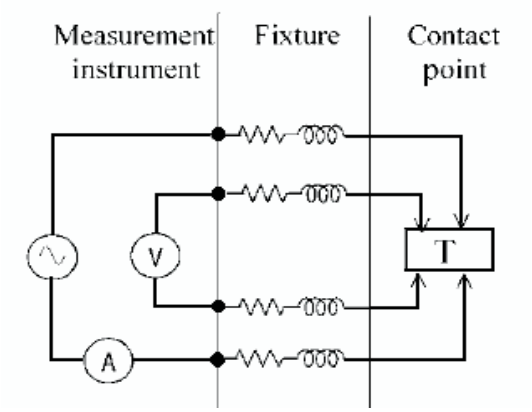
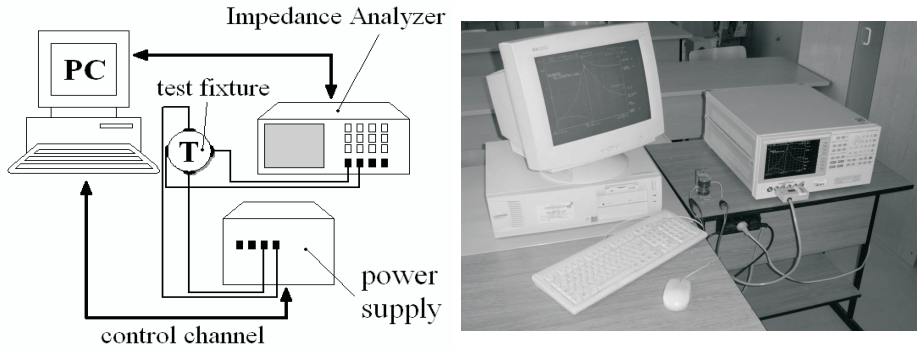


Fig. 7. Schematic diagram of four terminal measurements.

Conventional method used for bioimpedance measurement is a four-electrode method [7]. The current is injected into the sample through one pair of electrodes and the other pair of electrodes is used to measure the resulting voltage drop. If no current flows through the voltage measurement electrodes there is also no voltage drop across these electrodes and the measured voltage is the same as the voltage under the electrodes.

6 Measurement System Elements

The system architecture and outlook are presented in Fig. 8(a) and 8(b). The system contains: Impedance analyzer, measurement test fixtures, personal computer and additional power supply block. Main block requirements are discussed as follow here.



(a) (b)

Fig. 8. Impedance measurement system scheme (a) and outlook (b)

6.1 Impedance analyzer

The heart of the system is Agilent Technologies 4294A precision impedance analyzer with: frequency range 40 Hz - 110MHz. impedance range 10mΩ - 100MΩ. The test signal level range is 5mV to 1V rms or 200μA to 20mA rms, DC bias range is 0V to $\pm$40V or 0mA to $\pm$100mA, accuracy $\pm$0.08%.

6.2 Test fixtures

The test fixture plays an important role in impedance measurement in both mechanically and electrically. The quality of the fixture determines the limit of the total measurement quality. The contact terminals of the test fixtures is 4-terminal that are suited to different applications. Key points to consider when fabricating a test fixture are:

1. Residuals must be minimized. To minimize the residuals, the 4TP configuration should be maintained as close as possible to the tested object. Also, proper guarding techniques will eliminate the effects of stray capacitance.

2. Contact resistance must be minimized. Contact resistance will cause additional error, it directly affects the measurement result. The contact electrodes

should hold the tested object firmly and should always be clean. Corrosion-free materials for the electrodes are used.

3. Contacts must be able to be opened and shorted. Open/short compensation can easily reduce the effects of the test fixture residuals. To perform an open/short measurement, you must open and short the contact electrodes. For an open measurement, the contact electrodes should be located the same distance apart as when the tested object is connected. For the short measurement, a lossless (low impedance) conductor should be connected between the electrodes, or contact electrodes should be connected directly.

Electrical investigations of biological materials are performed using two types of electrodes: conventional electrodes and microelectrodes. Microelectrodes allow small currents; hence, these electrodes are generally nondestructive to the solution and species under investigation. This advantage is significant in biological samples and for in vivo measurements, where such destruction should be eliminated. A commonly used impedance measurement device in biophysical investigations is the Electrical Cell-substrate Sensing (ECSTM) device [3]. The ECSTM impedance measurement device consists of a 250μm electrode and a counter electrode. Impedance changes due to the fractal motion of cells during their spreading and adhesion can be recorded as impedance changes [1–7]. Multiple electrode systems are also used for recordings of statistical data correlation in homogenous samples. For cells and tissues with anisotropic impedance distribution, this device can facilitate impedance data recording at several measurement points.

6.3 Power supply

Additional power supply is used for higher then ordinary voltages or currents specific test requirements.

6.4 Personal computer

Used for system elements control functions and measured data storage and processing. Also a signal correction, which is nowadays mostly done by digital signal processing

Further, the system may employ some sort of demodulation method or devices to measure the amplitude and the phase of a multiple contact pairs.

7 Electromagnetic Properties of Tissue

Electrical conductivity σ and permittivity ε are determinated, by measured current flow and applied electric voltage over the tissue sample. Analogous the magnetic fields permeability μ is measured. These properties are determined by measured bioimpedanse and known samples shape and sizes. In complex materials such as tissue, the distance scale of interest depends on the needs of a particular investigation. In that case the electromagnetic properties σ, ε and μ would be functions of frequency.

An electromagnetic field distribution numerical model of a 3D human tissue object is presented. Electromagnetic field distribution is investigated by FEM. Formulation using magnetic vector potential and scalar electric potential (A-V,A) is used. Object under investigation is a human thorax. Magnetic field source is a magnetic stimulation coil over the thorax region. The modeling is made by ANSYS software. This kind of model formulation is suitable for electromagnetic field investigations and treatment by outer field source, such as magnetic stimulation, defibrillation, impedance tomography and etc.

8 Problem Formulation

The electromagnetic field of the inspected 3D object is calculated using FEM magnetic vector potential-electric scalar potential formulation (A-V, A). Eqn.1

A detailed three-dimensional finite element model of the anatomy of the human thorax was built to assess the induced currents distribution by external magnetic stimulation. The electromagnetic field distribution in the non-homogeneous domain was defined as an internal Dirichlet problem using the finite element method. The boundary conditions were obtained by analysis of the vector potential field excited by external current-driven coils.

The (A-V, A) formulation has been used.

$$\mathrm{rot}\,(\frac{1}{\mu}\mathrm{rot}\boldsymbol{A}) + \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} - \mathrm{grad}\,V_\varepsilon\right) = \boldsymbol{J} \tag{1}$$

where $\boldsymbol{A}$ is the magnetic vector potential, V_ε is scalar electric potential and $\boldsymbol{J}$ is vector of the current density.

Domain scheme used for the model formulation is shown in Fig.9, where Ω is the whole domain, Ω_1 is the current source domain and Ω_3 is the stimulated tissue domain, in both domains the $\boldsymbol{A}$ and V_ε exists. Ω_2 is the surrounding free space with only magnetic vector potential distribution.

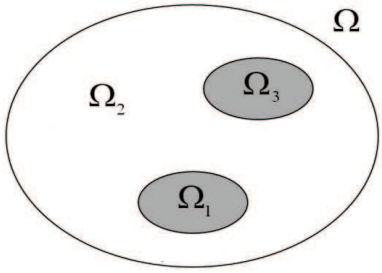
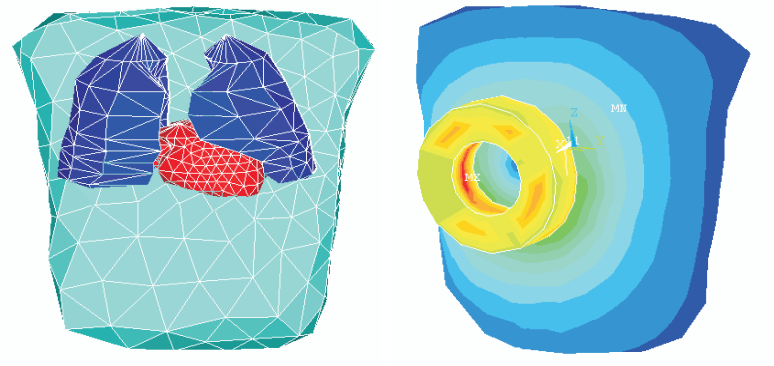


Fig. 9. Domain scheme used for the model formulation.

The finite element implementation of the A-V, A formulation has been carried out by using four-nodded, first-order, tetrahedral elements. The problem is solved by ANSYS software using solid97 elements with keyopt1 in Ω_1 and Ω_3 domains.

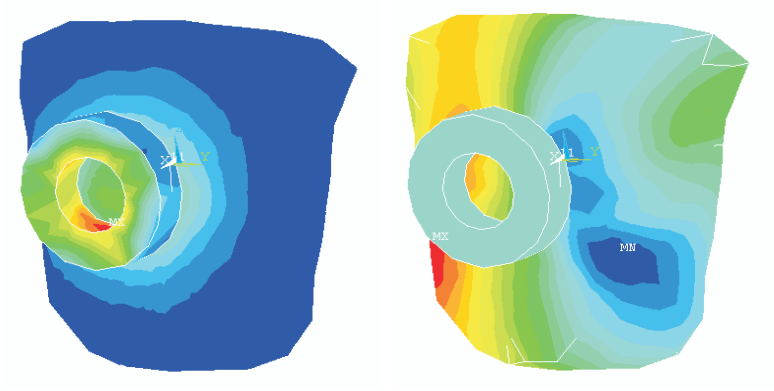
9 Results

Used 3D model of human thorax with some inner organs in it is shown in Fig. 10(a). Analyzed magnetic vector potential distribution is presented on Fig.10(b), magnetic flux density distribution is shown in Fig. 11(a), scalar electric potential distribution is shown in Fig. 11(b) and in Fig. 12 is shown magnetic flux density in heart volume only.



(a) (b)

Fig. 10. Thorax model (a) and magnetic vector potential distribution with stimulation coil (b).



(a) (b)

Fig. 11. Magnetic flux density distribution (a) and scalar electric potential distribution (b).

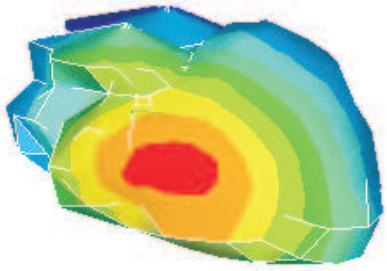


Fig. 12. Magnetic flux density in heart volume only.

10 Conclusions

The models, achieved by proposed method are suitable for electromagnetic field distribution calculations with FEM using ANSYS.

Concept of 4D model containing a time sequence of 3D models is developed. All models in the sequence have common mesh which is deformed for each time step object shape.

An experimental computer system for electromagnetic property measurements of biological objects is design. It employs Agilent 4294A precision impedance analyzer to measure the amplitude and the phase of a signal applied over a tested biological tissue sample. The frequency range from 40Hz to 110MHz is covered by Agilend 4294A impedance analyzer.

Data measured by the computer system can be used for tissue characterization,

electromagnetic properties determination and etc. in different frequency range.

Electromagnetic field distribution numerical model of a 3D human tissue object is presented. Electromagnetic field distribution is investigated by FEM with formulation using magnetic vector potential and scalar electric potential (A-V, A). This kind of model formulation is suitable for investigations and treatment by outer field source, such as magnetic stimulation, defibrillation, impedance tomography and etc. Quantitative results for field distribution in inner organs can be easily made.

Acknowledgements

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