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THE MAGNETIC FIELD OF THE HUMAN HEART MEASUREMENT, SIMULATION AND INVERSE PROBLEM

Hartmut Brauer, *Dept. EE & IT, Technische Universitaet Ilmenau, Germany*
Marek Ziolkowski, *Dept. EE & IT, Technische Universitaet Ilmenau, Germany*
Jens Haueisen, *Biomagnetic Center, Friedrich-Schiller-University Jena, Germany*

Invited Review Paper

Abstract: In cardiac investigations the magneto-cardiogram (MCG) is used for imaging the current distribution on the surface of the heart. This gives the cardiologist information about the area and location of infarctions and other disfunctions. The MCG provides this information noninvasive. This paper gives a brief overview of fundamentals of bioelectromagnetism and biomagnetic research followed by a description of the measurement technique for magnetic fields. The main goal of the paper is a short presentation of the state-of-the-art of inverse problem solving including cardiomagnetic phantom studies which we made recently.

1. INTRODUCTION

Biomagnetism is an interdisciplinary field of research with scientists working in medical, biological, psychological, physical, technical and other associated disciplines. Biomagnetic research ranges from basic neuroscience e.g. to uncover the function of the brain to clinical applications e.g. to monitor the foetal heart rhythm. The common denominator of all these research activities is the analysis of the magnetic field produced by the human body.

A major goal in the analysis of the measured bioelectromagnetic fields is the determination of the location of the source that produced the bioelectromagnetic field. This is called source localization or solving the inverse problem of biomagnetism. Source localizations require mathematical models the source itself and models of the body where the conductivity currents produced by the source are flowing, e.g. the human head or heart. This body model is referred to as volume conductor model. Given the two models (source and volume conductor), one can calculate the bioelectromagnetic field which was produced by the source at the positions of the sensors. This is called bioelectromagnetic field calculation or forward problem of biomagnetism. If the source model has free parameters (e.g. strength, location) a fit algorithm can be used to determine these free parameters in a way that they match the measured field distribution.

The solution of the inverse problem is not unique, i.e. there are several source configurations possible which can cause the same measured field. Hence, assumptions on the structure and the location of the source are helpful and necessary. For instance, a single current dipole is commonly used for the description of a focal source. Distributed sources are often modeled by dipole distributions. For the reconstruction of focal sources (usually an overdetermined problem) non-linear fit algorithms (e.g. Simplex algorithm, Levenberg-Marquardt algorithm) are employed. Dipole distributions lead to an underdetermined problem and are reconstructed using minimum norm estimations. Recently, also combinations of different inverse algorithms have been proposed.

2. FUNDAMENTALS OF BIOELECTROMAGNETISM

Several processes in the human (and animal) body are based on electrical activity. For example brain functions and heart functions are always connected to electrical activity. This activity is always accompanied by an electromagnetic field. The electromagnetic field consists of two parts: the electric field and the magnetic field. The electric field is measured with the help of surface electrodes, and it is known as Electroencephalogram (EEG) or Electrocardiogram (ECG). Biomagnetism deals with the measurement and the analysis of the magnetic field. The magnetic field is measured with the help of biomagnetometers. SQUIDs (Superconducting Quantum Interference Devices) are the most important part of biomagnetometers. Figure 1 presents the order of magnitude for different magnetic fields. Since the magnetic fields of the heart and the brain are very weak, a sophisticated technology is necessary to measure these signals [1].

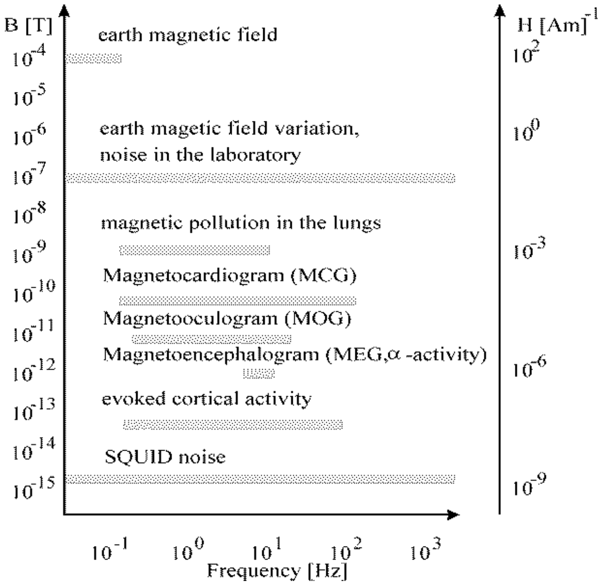

Fig.1. *Magnetic fields related to biomagnetism*

The biomagnetic data measured are used to determine the location of the electric source inside the body that produces the magnetic field and for signal analysis. One can determine the location and the strength of focal sources (e.g. a single current dipole) or the distribution and strength of extended sources (e.g. a current density distribution).

3. RESEARCH AT BIOMAGNETIC CENTER

The Biomagnetic Center at the Department of Neurology at the Friedrich-Schiller-University Jena is an interdisciplinary research center for basic and clinical research in the field of bioelectromagnetism.
At the present time 16 different groups from the Departments of Neurology, Neurosurgery, Psychiatry, Neuropediatrics, Pediatrics, Psychology, Physiology, Pathophysiology, Geriatrics, Cardiology, Gynecology, ENT, Physics and Biomedical Engineering perform investigations within more than 30 research projects. The common interest of the variety of different groups is to apply the advantages of bioelectromagnetic measurements to their specific field of clinical or basic research, i.e. to use this noninvasive method for source localization and signal analysis.

The research in the Biomagnetic Center can be divided into clinical and basic research.
Main points of the clinical research are:

- cardiology: myocardial viability diagnosis, risk stratification after myocardial infarction,
- neurology: spreading cortical depression in migraine patients, passive movement in stroke patients, abnormal brain activity in patients with glioma
- psychiatry: auditory processing in schizophrenics,
- gynecology: normal and abnormal fetal magnetocardiograms, normal and abnormal auditory processing during gestation.
- neurosurgery: presurgical mapping, tumor associated epilepsy

Main points of the basic research are:

- pathophysiology: spreading cortical depression in animals, propagation of penicillin induced spikes in animals,
- psychology: mechanisms of cortical plasticity, modulation of evoked primary sensory cortical activity by attention,
- neurology: somatosensory evoked high frequency activity, cortical plasticity, MEG-EMG coherence
- biomedical engineering: modeling, phantom investigations, stimulation systems

4. CARDIOMAGNETIC RESEARCH

Up to now there is no established noninvasive 3D-imaging procedure for the electrical excitation process of the heart in clinical cardiology. At the Biomagnetic Center Jena investigations of patients with myocardial infarction by precordial MCG mapping are done using a Philips biomagnetometer system. Each patient get a 3D-MRI dataset of the torso from which we construct a BEM model and use left ventricular myocardial surface for reconstruction of current density by a lead field depth normalized minimum norm solution for about 1500 reconstruction points. A typical result is presented below in a 3D-scenario with current density [$\mu A/mm^2$] using a color scale [8].

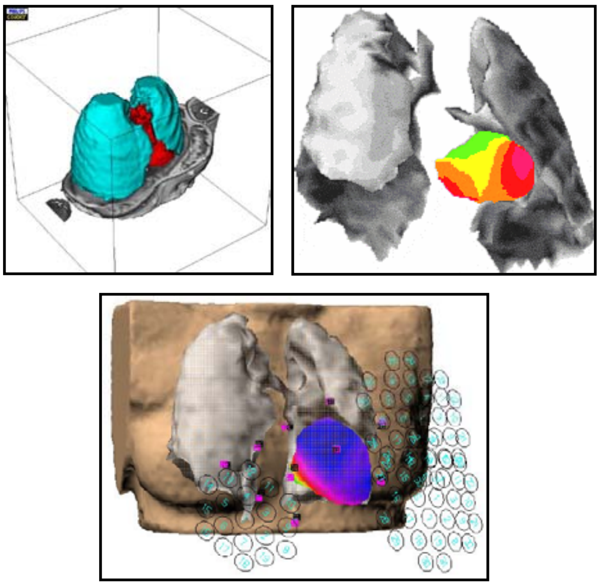

Fig.2. *Current distribution on the surface of the heart (colored) and representation of the lungs (gray).*

Results were compared to other cardiological procedures (left heart catheterization, thallium scintigraphy, echocardiography, 12 lead ECG) for localization of myocardial damage after myocardial infarction. Our inverse solutions show good correlation to other established procedures. We use it on a regular basis (one patient per week) for detection of viable myocardium. It's an alternative imaging procedure based on regional electrical activity that is closely correlated to cellular functions of myocytes. We feel that this procedure has the potential of a real clinical biomagnetic application.

5. MEASUREMENT OF BIOMAGNETIC FIELDS

The main research equipment available at the Biomagnetic Center consists of a 2x31 channel biomagnetometer (Philips) with 64 electric channels (Neuroscan) for human investigations (magnetically shielded room Ak3b, Vacuumschmelze) [1]

Fig. 3. *The 2x31 channel biomagnetometer system in the magnetically shielded room at Biomagnetic Center Jena*

and a self-developed 16-channel-Micro-SQUID-Biomagnetometer with 16 additional electric channels for basic investigations (magnetically shielded room from Amuneal) [9].

Fig. 4. *The 16-channel-Micro-SQUID-Device of the Biomagnetic Center Jena*

In both systems (human and basic research lab) magnetic and (invasive) electric recordings can be performed simultaneously. Access to a 1.5T Siemens and 1.5T Philips MRI (50 m away) is available.

6. PHANTOM EXPERIMENTS

Non-invasive functional localization of normal and pathological function of the heart is a major goal in bioelectromagnetic research. Numerous inverse techniques are used to achieve this goal. We build a realistically shaped human body phantom for experimental verification of these inverse solution techniques which are applied to magnetic (and electric) measurement data. Inside the phantom dipolar and extended physical sources are used to generate the fields. Magnetic field maps close to the phantom surface were recorded with the help of SQUID-based sensors, and body surface potential maps (BSPM) were recorded by means of surface electrodes. These data can be used to evaluate inverse techniques applied in bioelectromagnetics and other fields of research [5,6,3,10,2].

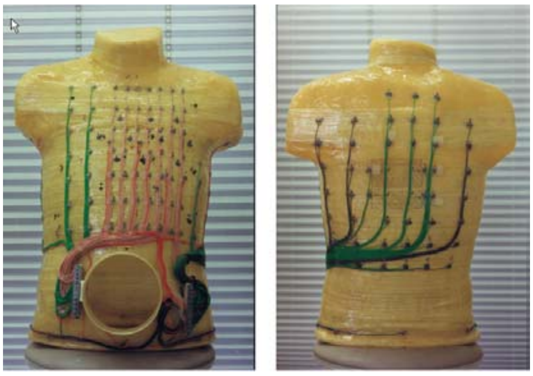

Fig. 5. *Frontal view (left) and back view (right) of our torso phantom*

Bioelectromagnetic measurement can provide electric and magnetic data sets for functional localization of heart or brain activity noninvasively. But the interpretation of measured, very weak magnetic fields generated by electrically active organs requires special (inverse) algorithms for localization or reconstruction of the sources.

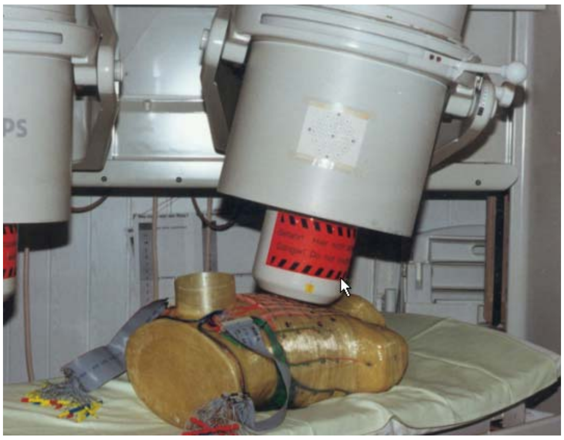

Fig. 6. *Biomagnetic field measurement applied to torso phantom*

This work is a collaboration between Jens Haueisen (University of Jena), Uwe Leder (University of Jena), Hartmut Brauer (Technical University of Ilmenau) and Uwe Tenner. The dissertation of Dr. Uwe Tenner is containing main parts of the phantom investigations [11].
Fig. 7 shows the measuring positions (electrodes, magnetic sensors) and the measured magnetic field map and the body surface potential map.

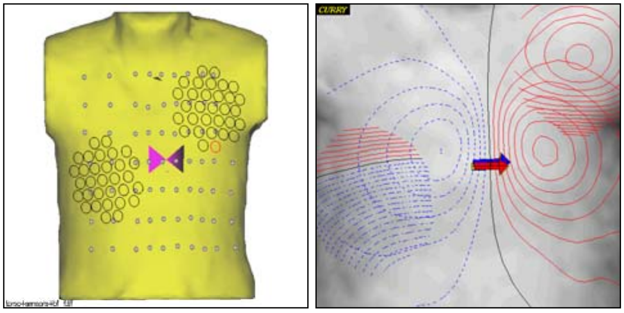

Fig. 7. *Phantom surface with the two magnetic sensor arrays (containing each 31 magnetic sensors), the 67 surface electrode positions, and the schematically shown positions of the extended current source. On the right-hand-sight the measured magnetic field map and body surface potential map is shown. The arrows indicate the equivalent current dipoles which can be estimated from these data.*

The main part of the phantom study was proposed as a new benchmark problem for inverse methods at the TEAM workshop during the COMPUMAG conference in Sapporo 1999 [4]. The International Compumag Society (ICS) accepted this proposal as the new TEAM Workshop problem 31. A complete set of measuring data can be downloaded from our webpage (http://www.biomag.uni-jena.de/) and may be used to verify own inverse techniques [7].

7. MEASUREMENTS AND SIMULATIONS

We measured the magnetic field distribution and electric surface potential distribution generated by an extended current source model which was placed in a homogeneous volume conductor (torso phantom) [5,6]. A current of 500 µA and a frequency of 25 Hz was impressed to the source model which was placed in an almost heart position inside the phantom. The source position was known due to *Magnetic Resonance Imaging (MRI)* measurements of the whole phantom. The magnetic field distributions were measured using the biomagnetometer system at the Biomagnetic Center Jena consisting of two separate dewars containing each 31 magnetic sensors.

To compare the different solution methods we defined an uniform source space which was the same for all series of simulation. It consists of a cube (in 3D case, Fig. 8)

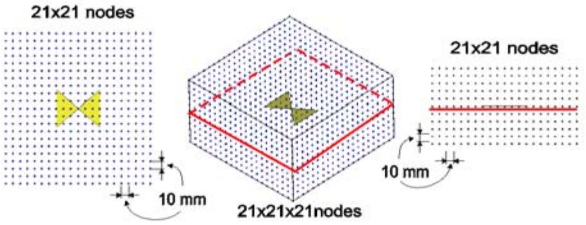

Fig. 8. *Regular cubic source space for current density reconstruction (3D case)*

containing a regular mesh of 21x21x21 nodes (spacing 10 mm), or it consists of a quadratic plane (in 2D case, Fig. 9) containing a regular mesh of 21x21 nodes (spacing 10 mm) defining the positions where current dipoles can be located.

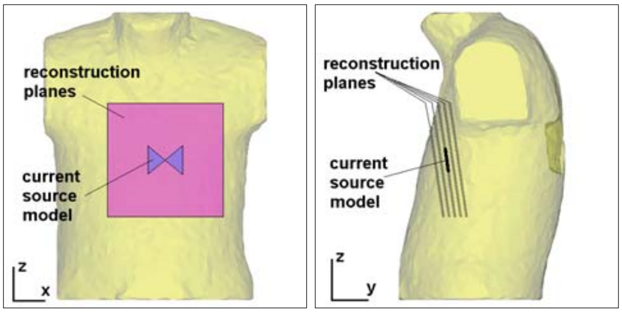

Fig. 9. *Torso phantom, physical current source model, and reconstruction planes (2D case).The coordinate system is indicated (x: right-left, y: front-back, z: down-up).*

Thus the positions are fixed and only their magnitudes and orientations can varying. Consequently, we have to solve a linear optimization problem.

8. BIOMAGNETIC SOURCE RECONSTRUCTION

There are a lot of different methods for solving the biomagnetic inverse problem already used in daily practice. Because usually minimum norm estimations are applied to the measured data we chose the following methods for testing with magnetic data measured for an extended current source placed inside a homogeneous torso phantom.

For given source locations, the lead field matrix $\boldsymbol{L}$ links the dipole component vector $\boldsymbol{j}$ with the forward calculated data vector $\boldsymbol{m_f}$:

$$\boldsymbol{m_f} = \boldsymbol{L\,j}$$

For optimal source parameters the squared deviation Δ^2 between the measured data $\boldsymbol{m}$ and the forward calculated data has to be computed and minimized.

$$\Delta^2 = 2\ \boldsymbol{m_f} - \boldsymbol{m}\ 2^2 = 2\ \boldsymbol{L\,j} - \boldsymbol{m}\ 2^2$$

Because this residuum usually not vanishes we have to regularize the problem. Regularization, like *Tikhonov regularization*, means adding a second term, the model term ***M(j)*** multiplied by the regularization factor ***8***.

$$\Delta^2 = 2\ \boldsymbol{L\,j} - \boldsymbol{m}\ 2^2 + \boldsymbol{8}\,2\ \boldsymbol{W\,j}\ 2^2 = \boldsymbol{D(j)} + \boldsymbol{8\,M(j)},$$

where $\boldsymbol{W}$ is a diagonal location weighting matrix. The L_p -norm in both data and modeling term yields

$$\boldsymbol{D(j)} = 2\ \boldsymbol{L\,j} - \boldsymbol{m}\ 2^{pd}\ ,\quad \boldsymbol{M(j)} = 2\ \boldsymbol{W\,j}\ 2^{pm}\ ,$$

with $1 \le p_{d,m} \le 2$.

We applied four different methods:

a) L_1 –norm: with pd = pm = 1

b) L_2 –norm: with pd = pm = 2

c) Low Resolution Tomography (LORETA):
L_p –norm with $\Delta^2 = \| \mathbf{L\,j} - \mathbf{m} \|^{pd} + \lambda \| \mathbf{B\,W\,j} \|^{pm}$,
where **B** is the Laplacian coupling matrix.

c1) LORETA-1: $\Delta^2 = \| \mathbf{L\,j} - \mathbf{m} \|^{1} + \lambda \| \mathbf{B\,W\,j} \|^{1}$

c2) LORETA-2: $\Delta^2 = \| \mathbf{L\,j} - \mathbf{m} \|^{2} + \lambda \| \mathbf{B\,W\,j} \|^{2}$

We tested all these methods by looking for an optimal regularization factor ***8***. In the case of L_2 -norm this optimal parameter was estimated applying the well-known L-curve technique.

Additionally, we compared the CDRs computed from magnetic data, electric data and the combination of both data. For the comparison of the CDRs we employed a visualization technique based on equivalent ellipsoids [12].

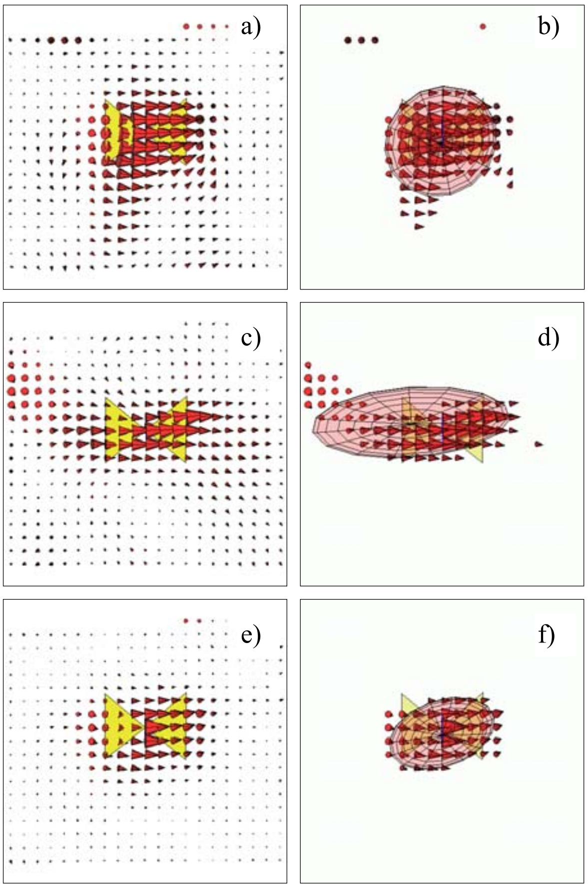

Fig. 10. *Current density reconstruction results on the plane coinciding with the current source model for electric (a, b), magnetic (c,d), and combined measurements (e, f). Left column shows the entire CDR while right column shows supraliminal CDR (30% threshold) together with equivalent ellipsoid.*

Fig. 10 demonstrates that the best reconstruction is received in the case of combined data (electric and magnetic).

Table I

Distance Between COG and Center of Current Source model for Different Reconstruction Planes

Used data	*Reconstruction plane* -20mm	-10mm	0mm	10mm	20mm
E	21.3	20.0	7.0	11.1	20.1
M	23.0	11.8	24.1	29.5	28.7
M+E	25.4	10.4	5.2	10.8	20.4

Table I shows the distance between the center of gravity of reconstructed supraliminal CDRs (30%) and the center of current source model for different reconstruction planes ("-/+" denotes plane shifting front/back, i.e. –y direction in Fig. 9) and different data sets (E electric, M magnetic, and M+E combined). The worse performance of reconstruction based on magnetic data can be attributed to the small coverage of the relevant field information. The smallest distance was found for the combined data and the plane coinciding with the current source model. In this case the dominant axes of the equivalent ellipsoid equal 81.8 mm and 49.8 mm which is in a good accordance with the dimensions of circumscribing rectangle covering the current source model (60 mm width, 50 mm height).

9. CONCLUSIONS AND OUTLOOK

In the paper the solution of the biomagnetic inverse problem was evaluated which is related to the TEAM problem 31. It was found that minimum norm least squares method are suitable for the inverse problem solution if the reconstruction plane is not far away from the true source location and both electric and magnetic measurement data are used. There was also presented an improved technique for postprocessing current density reconstruction (CDR) which will support statistical analyses and the visualization on the basis of equivalent ellipsoids. Although there were presented only limited examples, it is possible to apply this technique to other types of vector fields, too.

The 13th International Conference on Biomagnetism (world conference on Biomagnetism) in August 2002 will be organized by the Biomagnetic Center and held in Jena. The main objective of the 13th International Conference on Biomagnetism 2002 is to bring together scientists from around the world for extensive discussions and the exchange of results in the field of Biomagnetism.

Biomagnetism is an interdisciplinary field of research with scientists working in medical, biological, psychological, physical, technical and other associated disciplines. Biomagnetic research ranges from basic neuroscience e.g. to uncover the function of the brain to clinical applications e.g. to monitor the fetal heart rhythm. The common denominator of all these research activities is the analysis of the magnetic field produced by the human body (for further details see: http://biomag2002.uni-jena.de).

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