TIME VARYING CURRENT DENSITY DISTRIBUTIONS IN THE HUMAN HEART AND BRAIN

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A new method for visualizing and post-processing 3D time varying vector fields is presented. This method is based on equivalent ellipsoids fitted to these fields. The new technique has been tested on vector fields representing current density reconstruction results based on biomagnetic data from a cardiac patient and a neurological patient. Multiple foci in the vector fields are extracted by multiple ellipsoids which are fitted in an iterative manner. The new method enables visualization of even very complex vector fields, as well as statistical post-processing.

KEYWORDS: Magnetoencephalography, Magnetocardiography, Electroencephalography, Electrocardiography, Visualization

INTRODUCTION

Bioelectromagnetic measurements provide non-invasively information about the electrical activity within the human body. For example, Magnetoencephalography (MEG) and Electroencephalography (EEG) are used to assess electrical brain function, while Magnetocardiography (MCG) and Electrocardiography (ECG) provide information about the electrical heart activity. MEG and MCG are commonly measured without contact to the human body with the help of biomagnetometers using Superconducting Quantum Interference Devices (SQUIDs) as sensors\textsuperscript{1}. EEG and ECG are measured with the help of electrodes on the body surface. Based on these measurement data current density reconstructions (CDRs) are used to assess cardiac activation\textsuperscript{2} and brain function\textsuperscript{3}. CDRs are vector fields where each vector represents the current density in a volume element or on a surface element. Often CDRs are very complex containing several hundreds or thousands of single vectors and a data reduction method is needed to visualize these CDRs. Moreover, for statistical data analysis (e.g. in group studies) a method is needed which enables a comparison of time varying CDRs within groups of patients or volunteers. Previously, e.g. a parameterization based on the visual inspection of up to 8 sub-areas of the heart has been applied\textsuperscript{4}. These sub-areas have been classified manually into active or not active ones and statistics have been computed about the number of classified sub-areas. One clear disadvantage of this method is that it yields only a very rough statistical description of the location and extent of the activation maximums and minimums. In this paper, we expand a new technique which has been introduced previously for 2D planes\textsuperscript{5} to full 3D time varying problems. This technique is based on the parameterization of CDRs with the help of equivalent ellipsoids. The usefulness of our new technique is demonstrated with the help of two
examples. In the first example, data from a cardiac patient after myocardial infarction are analyzed. Here, the location and extent of the site of the infarction with respect to the origin and extent of so called late potentials, which occur after the QRS complex, are of clinical interest. The second example illustrates the new technique proposed in this paper using data from a neurological patient. This patient suffers from migraine and was measured during induced migraine related headache. The causes and mechanisms of migraine are not yet well understood. Thus, the investigation in this patient aims at the description of the electromagnetic phenomena related to migraine.

**EQUIVALENT ELLIPSOID TECHNIQUE**

An equivalent ellipsoid has been defined as a 3D ellipsoidal object fitted to a current density distribution region in which the magnitude of the currents is above a certain threshold. The threshold \( T_h \) used for marking the most important regions in the CDR has been defined empirically by \( T_h = 100\% \times (Q_{\text{max}} + Q_{\text{mean}}) / 2Q_{\text{max}} \), with \( Q_{\text{max}} \) being the maximum and \( Q_{\text{mean}} \) being the mean value of the dipole moments in the current distribution. Dipoles having a dipole moment greater than the threshold \( T_h \) are used for the fitting of the equivalent ellipsoid. The equivalent ellipsoid is defined by its three orthogonal semi-axes in a local coordinate system. First, the center of gravity of the marked region (COG) has been calculated. The position of the COG has been used as a new origin of the local coordinate system. The direction of the main axis has been computed on the basis of the weighted longest distance (LD) from the COG according to:

\[
\text{LD}_i = \sum_{i=1}^{N_T} M_i \left| \mathbf{p}_i - \mathbf{p}_{\text{COG}} \right|, \quad (1)
\]

where \( M_i \) denotes the magnitude of the moment of \( i \)-th current density vector and \( N_T \) is the number of current density vectors in the thresholded region. In the next step, the local coordinate system has been rotated so, that the main axis represents the \( z \)-axis. In the rotated coordinate system, the normalized position of the current density vector with the maximal distance from COG on the new \( x-y \) plane has been used as the direction of the second semi-axis of the equivalent ellipsoid. The direction of the third axis has been determined by the cross product of the first two axes. For multi-focal distributions the basic algorithm is applied iteratively, including an additional parameter, the separation radius \( R_s \). \( R_s \) selects a certain part of the thresholded CDR to which the equivalent ellipsoid is fitted. Using a local COG and \( R_s \), only the current density vectors within this restricted region are included into the fit of the equivalent ellipsoid. After the first equivalent ellipsoid fit, the second local maximum is searched in the rest of the thresholded CDR. Based on the separation radius and the new position of the local maximum the new local COG has been computed, and the next equivalent ellipsoid is estimated. The procedure is repeated until user break or up to the last current density vector in the thresholded distribution. The above described algorithm is applied to each time step separately in order to visualize time varying 3D CDRs.

**CARDIAC EXAMPLE**

The measurements have been taken in a magnetically shielded room (AK3b, Vacuumschmelze, Hanau, Germany) at the Biomagnetic Center in Jena, Germany. The magnetic field has been recorded with a twin dewar biomagnetometer system (2×31 channels) with first order axial gradiometers (Philips, Hamburg, Germany). We have measured the magnetocardiogram of a patient aged 70 years who had non-sustained ventricular tachycardia that developed after anterior left ventricular myocardial infarction and apical aneurysm. We have recorded 600 s of signals at a sampling rate of 1000 Hz. The last 40 ms of the bi-directional 30 Hz highpass filtered depolarization signal (late potentials, LP) have been used for inverse computations. Late potentials outlasting ventricular depolarization reflect a slow and inhomogeneous conduction in scarred myocardium and slow conduction as a requisite condition for reentrant ventricular arrhythmias. A 3D MRI data set of the chest of the patient has been obtained using a GYROSCAN® ACS II machine (Philips). Cardiac gated transverse slices (T1 weighted, 5mm) were measured and merged to a
three-dimensional torso data set. A Boundary Element model consisting of the left and right lungs as well as the outer torso surface has been applied for the magnetic field computations. The surface of the ventricle has been segmented from the MRI data set and subsequently used for the restriction of the source space. The current density vectors have been determined through a minimum norm least squares algorithm ($L_2$ norm) for all time points. This method selects the source configuration with the minimum sum of the squared current magnitudes. Since currents close to the sensors evoke larger magnetic signals than currents away from the sensors, a lead field normalization has been applied. This method removes the bias of the $L_2$ norm towards the reconstruction of superficial sources.

![Fig. 1. Magnetic QRS (a), butterfly plot of the terminal 40 ms of the bidirectionally 30 Hz highpass filtered depolarisation signal (LP).](image)

![Fig. 2. Equivalent ellipsoids found for different time steps in the LP interval, as indicated in Fig. 1](image)
Fig. 1 depicts the QRS signal and the bidirectionally highpass filtered signal. The time instants given in Fig. 1 indicate the instants at which the source reconstruction is presented in Fig. 2. The results in Fig. 2 show a mostly upper right (apical segment) activation maximum (position of ellipsoids). Sub-figure 4 in Fig. 2 is close to a minimum in signal strength and thus the CDR vulnerable to the influence of noise. Therefore, the equivalent ellipsoid for this instant in time is not representative. The mainly apical position of the equivalent ellipsoids in Fig. 2 agrees with the localization results obtained using the maximum CDR in Fig. 3.

![Fig. 3. Equivalent ellipsoids fitted to the reconstructed current density distribution located on the surface of the \( lv \) for the maximum mode. Diaphragmal view (a), apical view (b), and magnified apical view (c). The thresholded distribution is indicated by light cones.](image)

**NEUROLOGICAL EXAMPLE**

As a part of a larger study we have measured 31 channel DC MEG using the biomagnetometer described above in a patient with pharmacological induced migraine (nitroglycerin spray). The biomagnetometer has been positioned above the parietal-occipital cortex and one hour of continuous data with a sampling rate of 40 Hz (0 – 15 Hz bandwidth) has been obtained. Artifact rejection has been performed on the basis of the magnetic reference sensors, the electrooculogram (vertical and horizontal eye movements), and the electromyogram (musculus masseter and musculus trapezius). Large amplitude waves have been identified in the raw data and have been used for minimum norm estimation as described above. A 3D MRI data set of the head has been obtained, the inner skull surface has been segmented and triangulated (triangle size 7 mm), and a one compartment boundary element model has been constructed and applied for source reconstruction. The source model has consisted of 23564 current density vectors on the segmented brain surface (3.2 mm average distance).
Fig. 4. Results of the current density reconstruction for a patient with pharmacological induced migraine in side view (a) and enlarged side view (b,c). An equivalent ellipsoid with $R_s = \infty$ (b) and ellipsoids with $R_s = 12$ mm (c) fitted to the CDR.

Fig. 4 a depicts the entire brain and the reconstructed current density distribution. The thresholded CDR is given in Fig. 4 b and c, where this multi focal CDR can not be represented by a single ellipsoid as given in Fig. 4 b. The set of ellipsoids in Fig. 4 c approximates the thresholded CDR. The multiple ellipsoids indicated multiple sites of brain activation during this pharmacologically induced migraine headache. These multiple sites of activation support the theory of a spread of activation in migraine patients.

**SUMMARY**

We have presented a new technique for post-processing CDRs which will support visualization and statistical analyses. Although we have presented only examples from the field of biomagnetism, it is possible to apply our technique to other types of vector fields.

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REFERENCES