Analysis of Standard and Irregular Patterns in a Simulated Human Magnetocardiogram

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We present a study of current source reconstruction in MCG using a distributed current source model. We first test the efficiency of the inversion algorithm using a simulation model, selecting a short sequence of dipoles that generate dipolar magnetic fields. After adding noise to the calculated direct fields, the inverse computation is performed and the results are compared to the dipoles of the simulation data. The calculations are repeated with different levels of noise and different values of the regularization parameter, using only the normal components and all three components of the generated fields. The analysis of the magnetic field maps (MFM) sequence may help in identifying abnormalities during the ventricular repolarization. To assess the ability of the source reconstruction in detecting these disturbances, more complex simulation analyses can be performed, using a time series of dipoles that produces a sequence of MFMs as the ones generated by the normal heart activity. After introducing a perturbation in the activation of some dipoles in a specific region of the myocardium, inverse computation is performed to localize the heart activation inhomogeneities. The results show that 3D data allow finding a more accurate and stable solution.

Key words: magnetocardiography (MCG), inverse problem, regularization, correlation, conduction disturbances.

1. Introduction

Magnetocardiography is an electrophysiological study of the heart, since it measures its electric activity through the detection of the magnetic fields generated by the intracellular currents outside of the human body. If the MCG is recorded using a multi-channel system, the signals can be displayed in the form of a magnetic field map (MFM) that changes during the heart cycle. In case of a healthy subject, the myocardium fibers are activated following a well known sequence that produces a cardiac signal which has always the same characteristics, and the MFMs follow a well determined pattern. Patients suffering from cardiac pathologies, as myocardial infarction or cardiac heart diseases, show irregular patterns in different segments of the heart signal. The MFMs can be used to calculate the source that generates a given field distribution, but since the inverse problem has no unique solution, it is necessary to make some assumption on the source and conductor models. An approach in terms of an equivalent dipole source is applicable only for bioelectric activities confined in a small volume of the excitable tissue, but the measured magnetic fields arise from many distributed sources located in the heart volume. The results of the current source reconstruction (CSR) represent a model of the real current flow, and its reliability depends on the accuracy of the mathematical methods chosen, since special estimation techniques are needed to restrict the set of possible solutions.

In this study we investigated how reliable an approach in terms of distributed current source is to reconstruct the source that originates a defined dipolar magnetic field comparing the results of 3D data and normal components data, to evaluate what is the effect of the additional information provided by the tangential components. The analyses were repeated using a short time segment, to test the efficiency of the inversion algorithm, and using a longer and more complicated time evolution, specifically when the signals have a MCG-like waveform. Finally some disturbance was introduced in the simulation dipoles to model inhomogeneities in the activation wavefront. The analyses were performed using the experimental software MFIView of the BMDSys Gmbh (Jena, Germany).

2. Methods

2.1 Source Model

The heart activity can be modeled in many ways, but a distributed current source model is the one that better fits the physiological constraints. The activation is not localized in few sites, but involves periodically all myocardial fibers in one heart cycle, and can be described as a great number of dipoles with fixed locations and varying amplitudes. The problem equations are usually written in the form:

$$[L][J] = [B]$$

where $L$ is the lead field matrix that depends on the sensors system and on the dipoles positions, $J$ is the vector of unknown parameters, the vector moments in our case, and $B$ is the matrix of measured field values. The MCG systems currently used are multichannel...
systems that can measure simultaneously many field values, but the number of parameters to be found is usually much higher. Because of the underdetermined problem, minimum norm techniques are used to find the most plausible solution, that can be affected by measurement noise, thus requiring regularization to be stabilized, that is replacing the linear system by a nearby system which is less sensitive to the noise and considers the computed solution as an approximation of the real one. The equation to be solved is in the form of:

\[ (L^T L + \alpha I) J = L^T B \]  

Weighting of the matrix coefficients is also possible to emphasize the activation in a specific region of the source space, but for cardiac studies normal minimum norm or least square solutions can give already good results in the source localization.

The solution of eq. (2) depends on the parameter \( \alpha \): small values may correspond to solutions dominated by noise, whereas greater values may result in over smoothed solutions. Many methods have been proposed for an appropriate choice of the regularization parameter, but it has to be pointed out that too large values of \( \alpha \) may lead to stable but too incorrect solutions.

2.2 Conductor Model

The volume conductor model used is a boundary element method (BEM) model with linear potential approximation. The properties of the conductor model are approximated by a series of realistically shaped compartments, each one characterized by a constant isotropic conductivity, and the magnetic field outside is completely determined by the potential at the interfaces with different conductivities. The model used has four compartments (Fig. 1): torso, heart and lungs, obtained from a CT data acquisition, described as discretized surfaces divided in triangular meshes (about 600 triangles for each surface). The conductivities assigned to torso, heart and lungs were respectively 0.2, 0.6 and 0.05 S/m, in agreement with the literature.

Fig. 1 BEM conductor model including torso, heart and lungs.

2.3 Sensors System

In Fig. 2a and 2b the sensors configuration used to simulate the magnetic field values, corresponding to the MCG system installed at the Tokyo Denki University (TDU), is shown. The system uses second order gradiometers, orthogonal wound on a rectangular solid 3x3x6 cm, and is able to record simultaneously three-dimensional magnetic fields.

Fig. 2 Coordinate system for MCG (a) and 3D second order gradiometer (b).

3. MCG Data

3.1 Simulation Data

The source space region was divided in 292 voxels, and at each one was assigned a dipole with defined position. The moments of the dipoles may vary in time, so that is possible to follow the activation wavefront inside the heart volume. As it is shown in the flowchart in Fig. 3, three types of simulation data are used.

Fig. 3 Flowchart of data analysis.

3.1.1 Short sequence of data

First a short sequence of dipoles is selected to test the inversion procedure without a heavy computational burden. The dipoles vary slowly in a 10 ms interval and at each time instant the magnetic field produced by these dipoles is calculated. Then noise with Gaussian distribution is added to the field, to simulate real conditions, when the recorded signals are perturbed by
environmental noise. Finally the source reconstruction is calculated and the fitted dipoles are compared to the ones that originate the signals.

Fig. 4 Magnetic field calculated at the sensors locations (a) and magnetic field having a S/N ratio = 5 (b).

3.1.2 Long sequence of data
A second series of simulations is performed when the signals last for a longer time segment (more than 300 ms), using a more complicated sequence of dipoles, so as to obtain signals having a morphology similar to a typical MCG. The dipoles change widely in directions and amplitudes, as it is shown in Fig. 5. The data have a 1 ms interval scale.

Fig. 5 Dipoles distribution at QRS (a) and T max (b).

3.1.3 Noise added in dipoles amplitudes
In the last series of analyses, perturbations with random distributions were added to the dipoles of a selected region to simulate irregular patterns during the heart excitation. The portion of the heart volume was about 15% of the total volume. In Fig. 10 the orientation difference of the average dipole during the ST segment is shown, and in Fig. 11 the relative difference between the average dipoles amplitudes.
defined in eq. (3), where $J^s$ and $J^r$ are respectively the moments of simulation and reconstructed data is plotted:

$$\text{RelDif}(t) = \frac{\text{abs}(\overline{J^s} - \overline{J^r})}{\text{max}(\overline{J^s}, \overline{J^r})}$$  (3)

$\text{RelDif}(t)$ is the relative difference between the moment vectors $J^s$ and $J^r$.

![Figure 9](image)  
**Fig. 9** Selected dipoles of simulation data (a) and after adding disturbances in the dipoles amplitudes.

Figure 10 shows the orientation difference in degrees (with trendline) of the average dipole before and after adding noise to the amplitudes. The data is plotted against time in milliseconds.

![Figure 10](image)  
**Fig. 10** Orientation difference in degrees (with trendline) of the average dipole before and after adding noise to the amplitudes.

Relative difference in the average dipole amplitude (with trendline) as absolute numbers, before and after adding noise to the moments.

![Figure 11](image)  
**Fig. 11** Relative difference in the average dipole amplitude (with trendline) as absolute numbers, before and after adding noise to the moments.

### 3.2 Source reconstruction

After adding noise to the calculated fields, CSRs are performed using different values of the alpha parameter in eq. (2) and varying the S/N ratio of the signals, to study the effect of the regularization at different noise levels. A correlation parameter, based on the equivalent dipole of a set of dipoles, is used to quantify the difference between two distributions:

$$c_{\text{cor}}(t) = \frac{\sum_{i=1}^{N_T} \left( \overline{J^s}(t) - \overline{J^r}(t) \right) \left( \overline{J^s}(t) - \overline{J^r}(t) \right)}{\sqrt{\sum_{i=1}^{N_T} \left( \overline{J^s}(t) - \overline{J^r}(t) \right)^2} \sqrt{\sum_{i=1}^{N_T} \left( \overline{J^s}(t) - \overline{J^r}(t) \right)^2}}$$  (4)

where the vectors $J$ are the averages of all moments, the symbols $\langle \rangle$ are the averages of $J$ over the whole time segment of length $N_T$, the vector $P = P^{\text{rms}}$ is the distance between the two centers of mass, and $D_{\text{max}}$ is the maximum axis of the source space model. Since the simulation data are represented by a set of dipoles that are used to calculate the MFMs, and the final result is expressed by a distribution of dipoles in the same positions, the coefficient defined by eq. (4) guarantees an estimate of their similarity, and thus it is a measure of the relative error in the source localization.

### 4. Results and Discussion

The localizations were repeated for 8 alphas. Smaller values of alpha guarantee a solution closer to the real one, but are more dependent on the noise level. To find an acceptable compromise between a stable solution and a more realistic one, the values are chosen from the same order of magnitude of the lead field matrix that appears in eq. (1), up to two orders of magnitudes bigger.

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Table 1: Alpha values of eq. (2), for normal and vector components data.

In the tests performed with high values of the S/N ratio using a short dipoles sequence, the correlations show good results, proving the validity of the inversion procedure. For an S/N ratio value of 5, the correlation values defined in eq. (4) start decreasing significantly, and the differences between planar and 3D data become more emphasized, since the range of variation is larger for normal components data.
The results change abruptly when considering a dipoles sequence that generates signals as in Fig. 6. In this case the dipoles change drastically amplitudes and directions. Since a planar system is mainly sensitive to tangential currents, it is not able to follow dipoles whose directions vary from tangential to normal and vice versa. The S/N ratio used to calculate the CSRs were 5, 10, 20, 40 and no noise, and the time intervals chosen were the QRS, T wave and the whole signal. In Fig. 18 the dipoles of both simulation data and reconstructed data are shown for a single time instant. The normal components data do not localize the source with good accuracy already for low values of alpha, whereas the 3D data show results similar to the previous ones, but the numerical values of the correlations are slightly lower. The S/N value does not affect significantly the results in all tests performed.

These analyses were also repeated for a short time segment and for the longer one. In the case of a short segment, the correlations calculated only for the altered dipoles show still good results if the amplitudes of the disturbances are not too big, with better numerical values in case of 3D data, and they are relatively independent on the alpha values and on the noise added to the field.

In the last series of tests, disturbances were introduced in the dipoles (Fig. 9), the direct field is calculated, noise is added to the field and the inverse solution is computed. The energy ratio between the added perturbation and the simulation data dipoles is defined as:

\[ \text{Energy ratio}_i = \frac{\sum_{j=0}^{K} |\vec{J}_i(t)|^2}{\sum_{j=0}^{K} |\vec{J}_j(t)|^2} \]  

where \( J_N \) is the noise vector, \( J \) is the moment for the \( i \)th dipole and \( T \) is the segment time length considered. The average value is considered for all dipoles.

When the signals were generated by the longer dipoles sequences, the CSR was performed in the ST segment, and in this case as well, the results are drastically different for normal and vector data. For the 3D data, the correlations are still good, but become lower as the added perturbations and alpha values increase. In case of considering only the dipoles where the noise was introduced, the values are sensibly lower but show a clear dependency on alpha. The normal components data do not allow finding a good solution comparable to the one obtained using the 3D data.
5. Conclusions

In localization studies using distributed models, the choice of the regularization parameter is usually done by using some minimization function or graphical method\(^5\). In the present study we compared the simulation data dipoles and the reconstructed ones by means of correlations values that express the degree of their similarity.

The analyses performed on a short interval show that the regularization has not a strong influence until low values of the S/N ratio are used. For higher noise levels, the correlations become progressively lower, but for vector data the range of variability is not so large, thus implying that by using vector data it is possible to find a stable solution without requiring a too high value of the regularization parameter.

When the fields are calculated using a much more varying sequence of dipoles for a prolonged time, the vector data allow finding a solution which is more reliable than the one that could be obtained by using normal components data. It is interesting to note that after adding noise to the direct field, the CSRs are relatively not affected by the S/N ratio.

A comparable result is obtained when computing the CSRs after adding noise to the dipole moments. Alpha values and field noise have a low effect on the CSRs, particularly on 3D data, and the factor that mainly affects the correlations is the entity of the disturbance in the dipole amplitudes. In case of using the longer signals, the added perturbations have still a strong influence on the CSRs, but an appropriate choice of the alpha parameter is also important to find a good solution.

In summary, 3D data give better results in the source reconstruction, especially when considering dipoles with widely changing directions and amplitudes, thanks to the sensitivity to the normal components of the currents, which is not allowed by a planar system. Further studies are needed to evaluate the accuracy of the localization with measured MCG data.

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References