Non-Invasively Measured Cardiac Magnetic Field Maps Improve the Estimation of the Current Distribution

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Abstract

Comprehensive body surface potential mapping (BSPM) and magnetic field mapping (MFM) measurements have been carried out in order to improve the estimation of the current distribution generated by the human heart. Electric and magnetic fields and also the planar gradient of the magnetic field during the QRS complex were imaged as a time series of field maps.

A model of the current distribution should explain the features of both BSPM and MFM. Simulated maps generated by a single dipole or a straight line source could be fitted satisfactorily to the BSPM, but not to the MFM. Electric potential and magnetic field maps simulated on the basis of a curved line source model are in good agreement to the measured maps. Also, curved structures in the gradient field maps are in accordance with the curved line source model. The good agreement of this model to simultaneously measured electric and magnetic data indicates the presence of a curvature component in the current density distribution. This is even more evident in the maps of the planar magnetic gradient field.

1. Introduction

Current sources in the myocardium can be investigated by measurements of the electric potential and magnetic field components. The importance of anisotropy and inhomogeneity of the conductivity in the cardiac tissue was pointed out recently [1, 2]. The excitation front in the heart forms an extended current source of complex structure, the geometry of the corresponding current field depends on the fibre orientation of the cardiac tissue. We have investigated the influence of these structures on the electric and magnetic field for a few simple configurations. Based on the theory of the electromagnetic field, differences between the information content of ECG and MCG in dependence on the current source configuration become evident.

2. Methods

2.1. Measurement

The cardiomagnetic field of three healthy volunteers has been investigated using a 63-channel SQUID device and a multichannel BSPM set-up. In a sequence of ten measurements, the B_z component of the cardiac magnetic flux density was measured at 136 positions at the front side and on 136 positions at the back side of the thorax as illustrated in Figure 1. In addition, B_x- and B_y-components were recorded at 2x70 positions. The electric potential was measured at 148 electrode positions. The sequential recordings were combined to an integrated data set using electric and magnetic reference leads for synchronization.

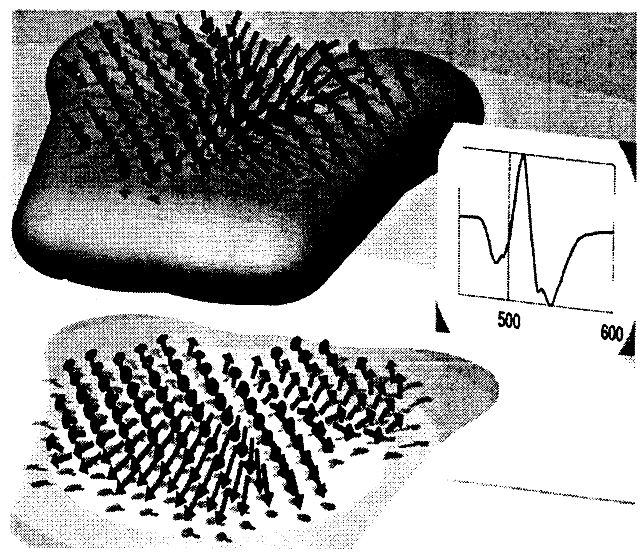

Figure 1. Cardiac magnetic field measured at 206 positions of the front side and at 206 positions of the backside. Note that in addition to the B_z-component also B_x- and B_y- components were recorded.

2.2. Models

The effect of anisotropic conductivity in a muscle fibre is modelled by an extended line source. To study the influence of different shapes of the line source, we have calculated the magnetic field and the electric potential of a straight line source and a curved line source.

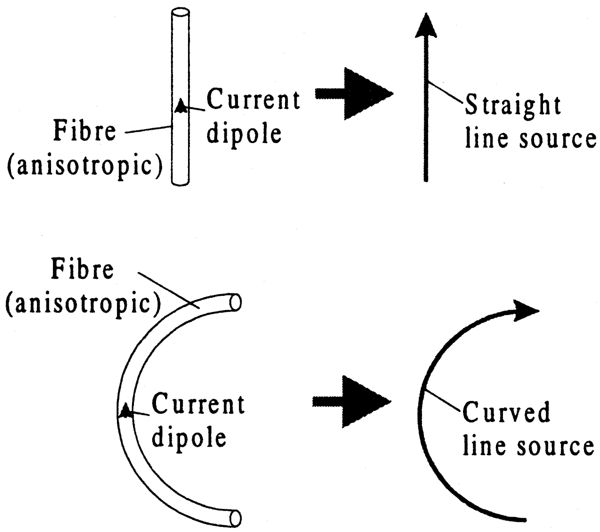

Figure 2. Modelling of anisotropic fibres by line sources

The current path of a single dipole source in a muscle fibre is concentrated to the path of the fibre if the conductivity in direction of the fibre is much higher than in the radial direction. The restriction of the current path of a single dipole source in a straight or a curved muscle fibre is approximated by a straight or a curved line source shown in Figure 2.

2.3. Numerical simulations

According to the electric and magnetic measurement the numerical simulations were carried out using a BEM model of a human torso [3]. The electric potential is calculated in the 434 nodes of the torso boundary. The potential differences in the numerical calculations are related to the potential near the right leg to concur with the conditions of the measurement. The magnetic field is calculated in two arrays of 9x9 sensors, one at the front side and another at the back side of the torso.

2.4. Planar gradient

A further method to visualize details of magnetic measurement data sets is to calculate the planar gradient of the B_z component [4]. The 2D-vector field represented by arrows is given by:

$$arrow = \left(\frac{\Delta B_z}{\Delta y}\right)\vec{e}_x + \left(\frac{-\Delta B_z}{\Delta x}\right)\vec{e}_y .$$

3 Results

At the beginning of the QRS the measured magnetic field is similar to the field pattern of a single dipole source. Later, close to the R-peak, when the depolarisation wave leaves the septum and arrives at the outer parts of the myocardium the magnetic field shows a more complex structure. In the following maps this time near the R-peak is taken.

3.1 Electric data

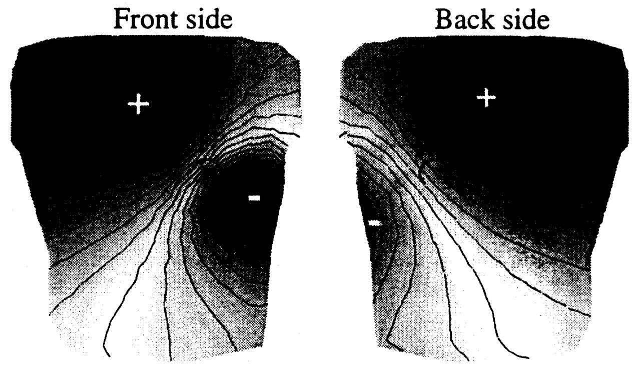

Figure 3. Simulated distribution of the electrical potential on the thorax (1 isoline corresponds to 0.1V)

The numerical simulation was done to find comparable distributions of the electrical potential and the magnetical field component of measured cardiac data during QRS complex. Identical electrical potential distributions were obtained in the simulations for both a straight and a curved line source as shown in Figure 3, which fit well to the measured electrical data (Figure 4).

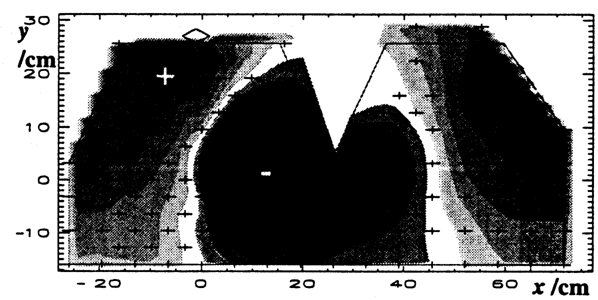

Figure 4. Measured distribution of the electrical potential during QRS complex (1 isoline corresponds to 0.1V)

3.2 Magnetic data

The measured precordial magnetic field component B_z (Figure 5a) exhibits an asymmetric field pattern with a pronounced extremum (+) below the zero line and a more distributed extremum (-) in the upper part.

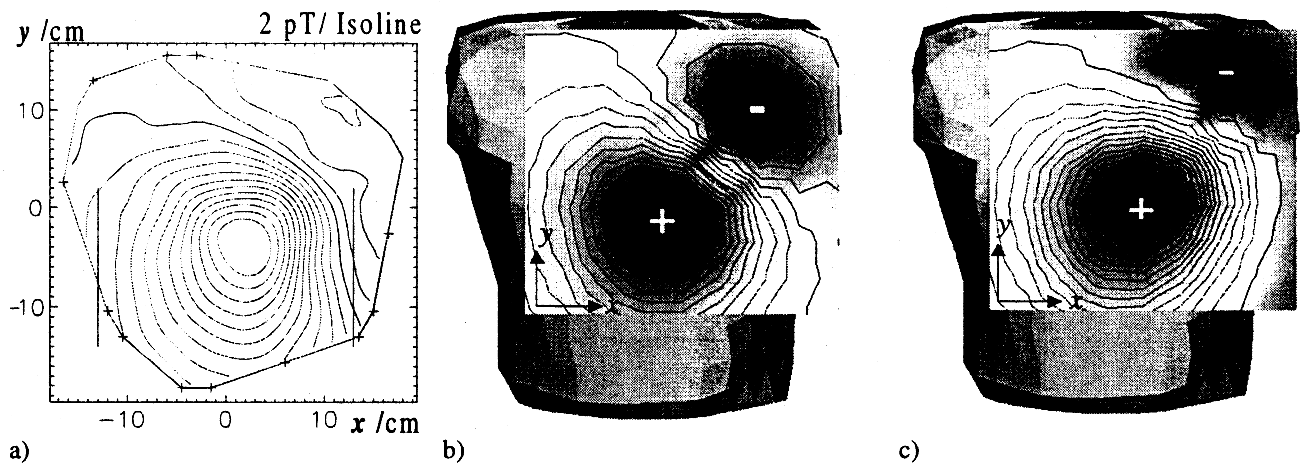

Figure 5. a) Measured and b),c) simulated distribution of Bz component of the magnetic flux density during the QRS complex at the front side of the thorax with b) straight and c) curved line source (1 isoline = 2 pT).

In contrast, the magnetic field component of the numerical simulation of the straight line source shows a more or less symmetric field pattern having two concentric extrema separated by a straight zero line (Figure 5b). On the other hand, the curved line source exhibits a minimum (-) in the Bz field which is more distributed above the curved zero line (Figure 5c). Furthermore the region with the highest field gradient is shifted from the zero line in direction to the maximum (+). Apparently, the measured map of Figure 5a) is better explained by a curved current source.

3.3 Planar gradient

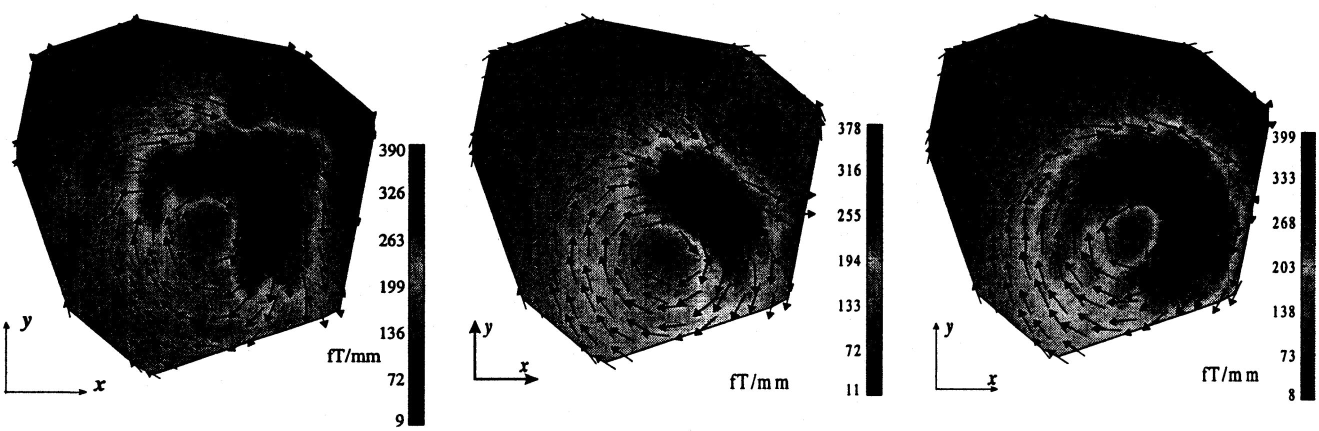

Figure 6. Planar gradient of
a) the measured B_z component b) B_z calculated for the straight line source c) B_z calculated for the curved line source

The feature in the magnetic map of a curvature component in the current density distribution are:

1. Asymmetric field extrema
2. Curved zero line
3. Shifted region of highest gradient from the zero line

Much more easily it can be shown in the maps of the planar gradient. The planar gradient in Figure 6 may be considered a blurred projection of the current density field to the sensor plane. The absolute value of the planar gradient is coded by the colours of the map.

Apparently, the vector pattern of the planar gradient of the measurement data shown in Figure 6a) is more similar to the pattern of the simulated gradient of the curved line source shown in Figure 6c). This may be considered a further indication of a curved current field.

Similar magnetic field features were found for all three volunteers: In the overview of Figure 7 the map of the B_z-component during QRS-complex of all three volunteers are shown. In all three cases, the corresponding planar gradient of the B_z- component in Figure 8 indicates the presence of a curvature component.

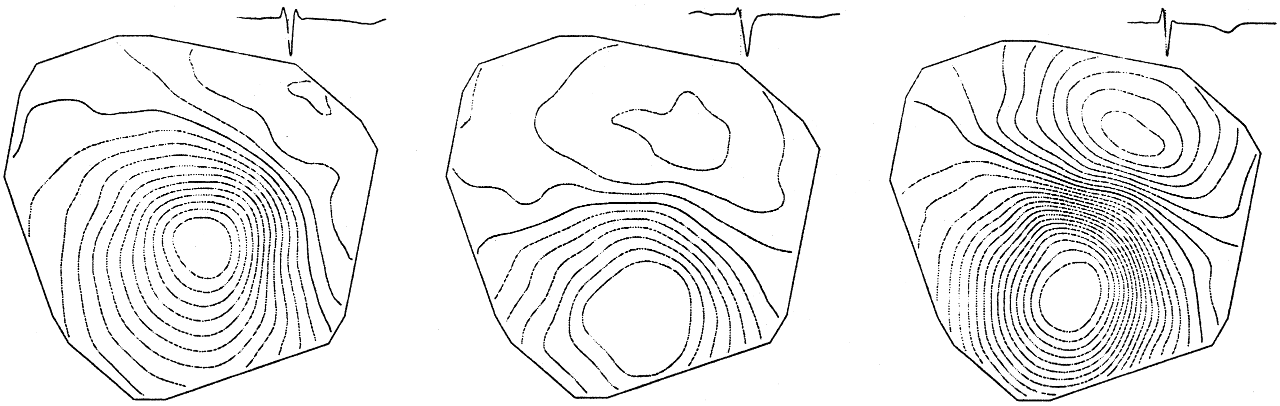

Figure 7. Map of the B_z component during QRS- complex of three volunteers (1 isoline = 2 pT).

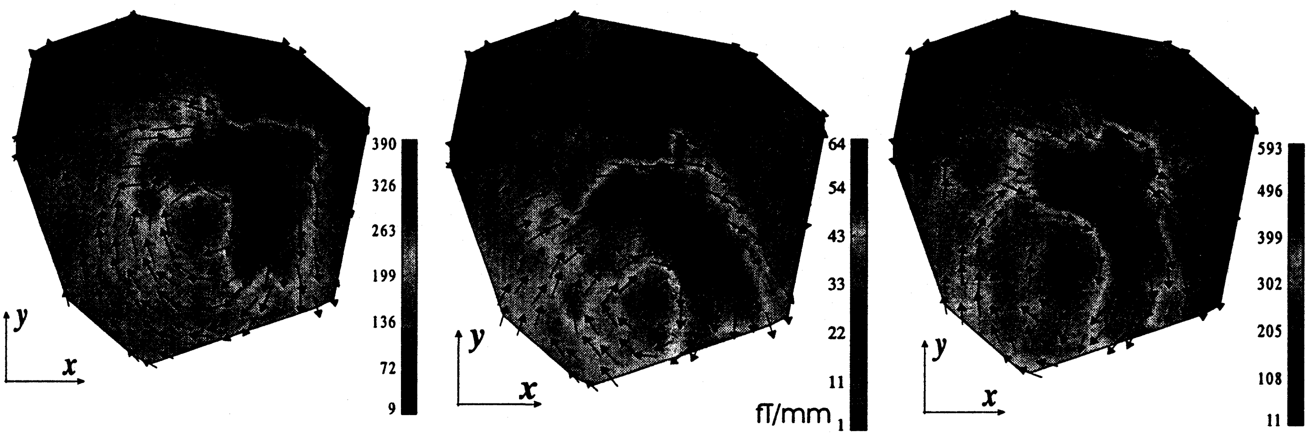

Figure 8. Map of the planar gradient of the three volunteers.

4. Discussion

The electric potential at the surface is particularly sensitive to the volume conductivity close to the body surface. In contrast, the magnetic field is due to the current distribution in the whole body. The magnetic field provides important details about properties of the field sources which are not displayed in the electrical potential on the body surface. This applies in particular to a situation where curved or circular currents are involved.
The curved line source model used here is a simple way to describe the current density distribution in the heart influenced by the inhomogenious and anisotropic conductivity of the myocardium. The good approximation of simultaneously measured electric and magnetic data provided by this simple model indicates the presence of a curvature component in the current density distribution.

Acknowledgements

This work was supported by the BMBF in the project 01Kx9912/8.

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