Cardiac multichannel vector MFM and BSPM of front and back thorax

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1 Introduction

Recent advances in development of low-Tc SQUID multichannel system have made it possible to perform magnetic field mapping (MFM) over the whole chest. They are easy to use and are installed in some university hospitals to provide high resolution temporal and spatial information of cardiac function in clinical studies [1].

To further investigate the spatial field properties, we have performed MFM over a large area near the front and the back thorax with a dense sensor grid. The horizontal components of the heart magnetic field were also recorded. For four volunteers, x-, y-, and z-components of the cardiac magnetic field were measured over a planar area of about 37 cm diameter. Simultaneously, a body surface potential mapping (BSPM) was recorded.

2 Methods

2.1 MFM measurements

MFM measurements were performed using SQUID multichannel system [2] installed inside a magnetically shielded room in the Klinikum Benjamin Franklin, Berlin. This system consists of 49 first order gradiometers for normal components of magnetic field (B_z) arranged in hexagonal lattice on a plane covering a circular area of diameter 21 cm, 14 gradiometers in tangential direction (B_x and B_y) and 7 B_z gradiometers on a plane 7 cm above the first plane. MFM over a larger area of diameter 37 cm were obtained by positioning the SQUID system at five positions over the front and five positions over the back side of the thorax. Fig. 1 shows schematic layout for the MFM measurements. The first measurement was performed with SQUID system in the central position, four measurements were performed in shifted positions. The SQUID system was shifted from the central position in such steps, that 21 B_z gradiometers on the first plane covered new area above the thorax, while other 28 B_z gradiometers occupied the same measurement sites as in the central position.

2.2 BSPM measurements

BSPM measurements were performed with 32 electrodes (Gold plated cup electrodes, Grass instrument Corp.). To obtain denser distribution of electrodes, five different configurations were used. Fig 2 shows BSPM layout, based on a 16×6 equally spaced rectangular grid with additional columns on the front and on the left back side region. For subsequent signal synchronization and averaging, the three reference electrodes remained fixed close to the heart region during all measurements. Altogether, electric potentials on 148 different sites around the thorax were recorded.

2.3 Protocols

During the measurements on four volunteers, the following steps were performed:

1. The BSPM grid was defined and plotted on the thorax (see Fig. 2)
2. The thorax surface and electrode positions were digitized with 3D-scanner.
3. The first electrode configuration was mounted.
4. The SQUID system was positioned in the central position above the front side of the subject's thorax, 12.5 cm caudal of the manubrium sterni.
5. The relative position between the thorax and SQUID system was measured by the 3D-scanner.
6. Five measurements were performed with SQUID system in positions shown in Fig. 1, which were obtained by shifting a bed with the subject. Simultaneously, the BSPM from the current electrode configuration was recorded.
7. Steps 3, 4 and 5 were repeated for the 2^{nd}, 3^{rd}, 4^{th} and 5^{th} electrode configuration. The MFM and BSPM with the current setup were performed.
8. The SQUID system was positioned in the central position above the back side of the subject's thorax. Steps 5 and 6 were repeated.

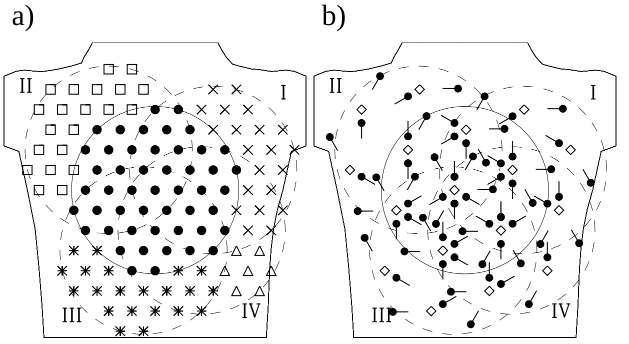

Figure 1: *Schematic view of 206 channel positions for the MFM layout above the thorax. a) 119 B_z channels in the first plane. Solid circle encloses measurement sites (●) in the central position. Dashed circles, I(×), II(□), III(∗) and IV(△), enclose measurement sites covered by the SQUID system in the four shift positions. b) 70 sites (●–) for B_x and B_y - small line indicates sensor's direction in the xy plane, and 17 sites for B_z gradiometers (◇) in the second plane.*

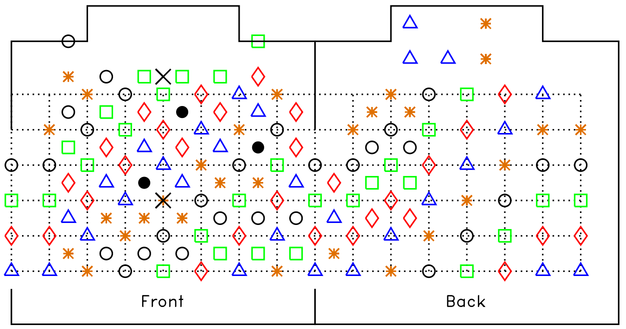

Figure 2: *Schematic view of 148 electrode positions for the BSPM layout. Different electrode subsets are labeled with symbols (○, □, ◇, △ and ∗), the three fixed electrodes with ●, and the manubrium and xiphoid with ×. Dotted lines show the basic 16×6 grid: horizontal and vertical steps are defined by the circumference of the thorax at the xiphoid level divided by 16 and by the distance between the manubrium and xiphoid divided by 3.5, respectively.*

Altogether 14 measurements were performed for each volunteer. Recording time was 50 s with sampling frequency 1000 Hz. The same bandpass filtering (0.016-250 Hz) was applied for magnetic and electric measurements. The total time for performing all measurement steps was 6-8 hours per volunteer. The most time consuming were steps 1 and 2 (together 2-3 hours) and mounting and checking of different electrode configurations (steps 3,4,5), which took 30-60 minutes per electrode set. The MFM measurement in five different positions in step 6 was the fastest (10-15 minutes).
Measured data was averaged in the following steps:

A From the reference electric channels, the most similar heart-beats in all 14 measurements were selected using the procedure described in [3].

B All 14 measurements were averaged using selected heart-beats from the step A.

C Averaged data from the step B were merged into one large data set that contained all magnetic and electric measurement sites.

For each of the four subjects, we constructed a data set for the averaged heart-beat combining

a) electric potentials from 148 sites with about 4 cm spacing on the chest and about 6 cm spacing on the back,

b) magnetic field values measured above the frontal thorax using 119 channels for B_z in a hexagonal lattice of 30 mm spacing for the first plane 4 cm above the thorax, 17 channels for B_z in a hexagonal lattice of 80 mm spacing for the second plane 11 cm above the thorax and 70 channels for B_x and B_y,

c) the same configuration as in b) but measured over the back side of the thorax.

3 Results

Figs. 3 and 4 show the time evolution of averaged signals during QRS-T segment in all B_z channels measured on the first plane from the front and the back side of the thorax, respectively. Polarity of the magnetic field on the back side is reverted in comparison with the magnetic field from the front side. Signal amplitudes are much smaller on the back side, because current sources within the heart are further away from the measurement plane in this case. Fig. 5 shows the MFM for B_z channels and BSPM for the R wave maximum. Corresponding vector MFM is displayed in Fig. 6. Comparison of MFM peak-to-peak values (Fig. 5a) on the front vs. back side gives 95.3 vs. 14.0 pT. The BSPM (Fig. 5b) shows clear dipolar-like structure both on the front and the back side of the thorax. On the other hand, the zero line of MFM on the back is shifted far away from the heart region. There is only one field extreme in that region. It is difficult to explain this map as being due to the dipolar-like current source alone. Possible explanations could be bent current sources [4, 5].

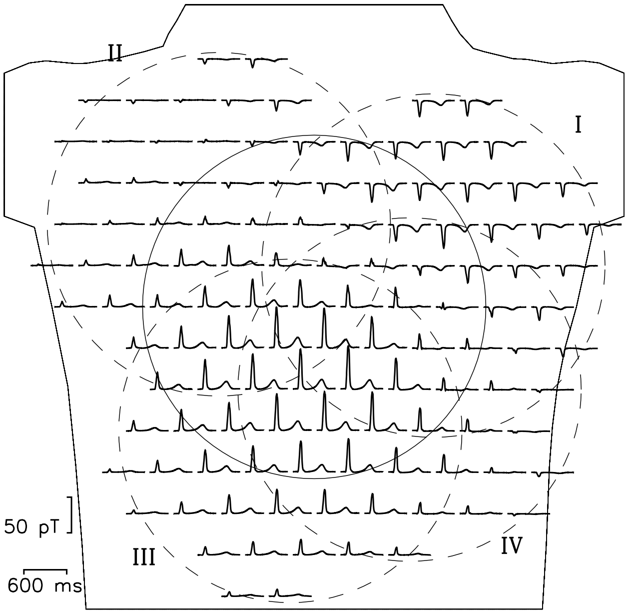

Figure 3: *The averaged time evolution of QRS-T segment above the front side of one volunteer. Signals are displayed exactly over the measurement sites (see Fig. 1a).*

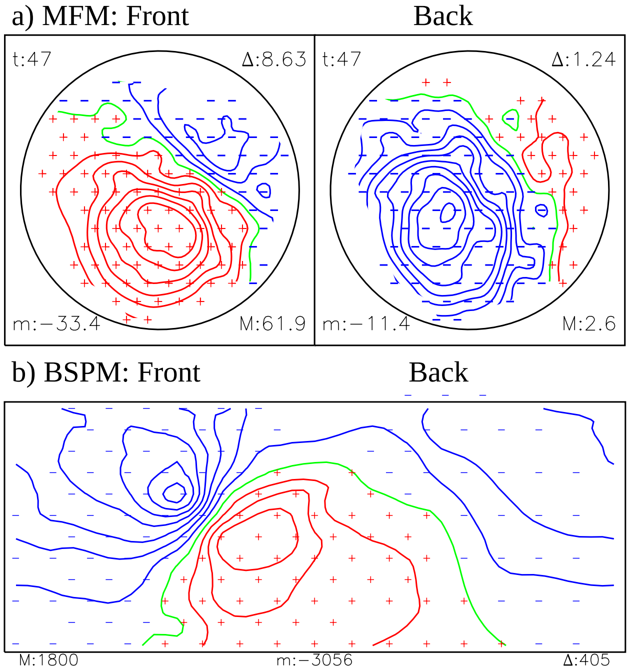

Figure 5: *a)The MFM (B_z channels) and b) corresponding BSPM for the R-peak. Here t denotes time in ms measured from the Q-onset, m and M are minimal and maximal map values and Δ step between two isolines. All these values are in pT and μV for the MFM and BSPM, respectively. Positions of measured sites are shown by $+$ and $-$ in accordance with the sign of measured data.*

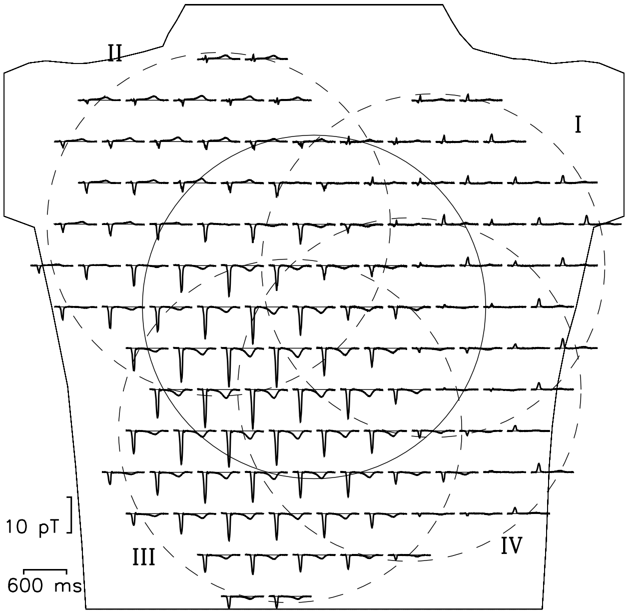

Figure 4: *The averaged time evolution of QRS-T segment above the back side of the thorax. Signals are displayed exactly over the measurement sites (see Fig. 1a). Notice the different vertical scale in Figs. 3 and 4!*

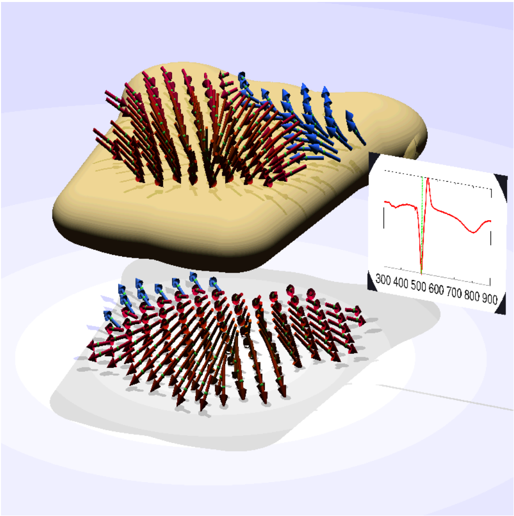

Figure 6: *The vector MFM for the R-peak above the front side (upper image) and the back side (lower image) of the thorax. Arrows represent magnetic field vectors composed of B_x, B_y and B_z components at measurement sites for B_z channels (Fig. 1a). Blue arrows mean in both images that the magnetic field vector is directed from the back to the front side of the thorax. Vectors were interpolated from all 412 gradiometer channels using the multipole expansion method [6] to convert recordings between different measurement systems.*

Fig.7 shows MFMs from single measurements in the central and four shifted positions (I, II, III, IV) of the SQUID system, which covered the area of 21cm. It is evident that some of this MFM does not contain all features shown by the corresponding complete maps in Fig. 5a, which covered the area of 37 cm.

In our layout for sequential magnetic measurements (Fig. 1), many of magnetic sites are repeatedly measured by different positions of the multichannel SQUID system. We estimated the quality of the final merged 119 B_z channel MFM by calculating the root mean square (RMS) and the maximum (MAX) differences between the measurements in the central position and the measurements in shifted positions, averaged over all 4×28 cases of covering the same site and over the whole heart-beat time sequence. For the data shown in Figs. 3 and 4, average RMS and MAX differences are 0.26±0.1 pT and 1.1±0.5 pT for the front side and 0.07±0.02 pT and 0.32±0.15 pT for the back side. Individual MAX differences were up to 3 pT and 0.7 pT for the channels in front and back side, respectively. These results show that the heart activity was quite stable during the different recording sessions and in that case merging of data did not influence the main MFM features. However, one has to be careful when using such data for analyzing some small change in MFM.

4 Discussion

Maps of B_z show that field extrema and other distinctive features of the MFM may be located at regions not covered by conventional multichannel MCG systems. The magnetic field maps in some time instants cannot be approximated by a current dipole source alone, because they show only a single extreme over the heart region on the back side of the thorax. The simultaneous BSPM exhibits a dipolar field character. The combined MFM and BSPM recordings provide a comprehensive data set for a comparison of electric and magnetic field properties under physiological conditions. It may be used to test and validate forward and backward calculation methods in the MFM and BSPM. The vectorial magnetic field information may help in the design of new multichannel MCG systems.

Acknowledgements

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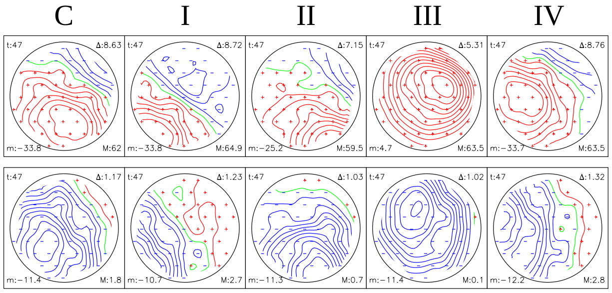

Figure 7: *The MFM for the R-peak, obtained from 49 B_z channels measured in central position (C) and four shifted positions (I, II, III, IV) of SQUID system above the front side (first row) and back side (second row) of the thorax.*

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