Performance of open cylindrical magnetic shield for magnetocardiograph using low-$T_c$ SQUIDs

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Abstract. We evaluated the performance of an open cylindrical magnetic shield for a magnetocardiograph using low-transition temperature (low-$T_c$) superconducting quantum interference devices (SQUIDs) so that we could miniaturize an entire magnetocardiograph system. The open magnetic shield was about 1 m in diameter and 2 m in axial length, and had a revolving door that provided easy access inside the shield as well as easy operation. The shielding factor for our magnetic shield was above 46 dB, and its distribution was uniform in the vicinity of the shield. The magnetocardiogram including the P-wave peak could clearly be measured with 64 axial gradiometers based on low-$T_c$ SQUIDs in the open magnetic shield. Typical distributions of myocardial ion currents of a normal subject were also obtained with the system.

1. Introduction

As the magnetic field generated from a human heart is typically less than several tens of picotesla [1, 2], it is usually measured with superconducting quantum interference devices (SQUIDs) [3, 4] in a magnetically shielded room (MSR). A conventional MSR, which consists of high-permeability material such as Permalloy and high-conductivity material such as aluminum [5-7], is usually a cube, about 2.5 m per side. This type of MSR performs exceptionally well and its shielding factor is above 50 dB. However, it accounts for a large share of the total volume and cost of a magnetocardiograph (MCG) system. Therefore, the magnetic shield for an MCG needs to be smaller and simpler.

In response to these requirements, several cylindrical magnetic shields for MCGs using high-transition temperature (high-$T_c$) SQUIDs have been reported [8, 9]. In addition, a cylindrical magnetic shield using a high-$T_c$ superconducting wire and flexible magnetic sheets has been reported [10, 11]. However, no cylindrical magnetic shields for MCG measurements using low-$T_c$ SQUIDs have been reported because of the size of the cryostat for liquid helium, even though low-$T_c$ SQUIDs are more sensitive and more practical than high-$T_c$ SQUIDs. The height of the cryostat for liquid helium is usually about 1 m, comparable to the diameter of a typical cylindrical magnetic shield for an MCG system. Consequently, there must be an opening through the surface of the cylindrical magnetic shield to install the liquid-helium cryostat, and this opening seriously deteriorates shielding performance.

In a previous study [12], we introduced an auxiliary magnetic shield around the opening and simulated its effect to resolve the problem. Moreover, we developed an MCG system using 64 low-$T_c$ SQUIDs and a cylindrical magnetic shield with an auxiliary magnetic shield. In this study, we will
discuss the structure and shielding properties of the magnetic shield we developed in detail. We will also present several kinds of magnetocardiogram data including current-arrow maps obtained with the MCG system we developed.

2. Structure

Figure 1 shows our magnetic shield. To develop an MCG system that provides easy access to a subject and easy operation, we designed an open magnetic shield with a revolving door and an auxiliary magnetic shield. The magnetic shield is about 2 m in axial length, about 1.2 m in outer diameter, and about 0.9 m in inner diameter. It is composed of three parts: a fixed part, a moving part (the revolving door), and an auxiliary magnetic shield.

Figure 2 shows an enlarged section of the fixed part and the revolving door in detail. An SUS (Steel Use Stainless) pipe with low permeability was used for the framework of the magnetic shield. The Permalloy sheets and the aluminum sheets were fixed on the framework and covered with buffer material and decorative sheets. The revolving door makes it easy for an operator to place a subject into the magnetic shield and adjust his or her position. Moreover, the two open ends can help to relieve a subject’s unease.

The auxiliary magnetic shield consists of two cylindrical magnetic shields made of Permalloy sheets that are 1-mm thick. The inner magnetic shield, which is magnetically coupled to the inner Permalloy layer for the fixed part, is 408 mm in diameter and 339 mm in axial length. The outer magnetic shield, which is magnetically coupled to the outer Permalloy layer for the fixed part, is 468 mm in diameter and 307 mm in axial length.

**Figure 1.** Open magnetic shield with revolving door and auxiliary magnetic shield.

**Figure 2.** Enlarged section of open magnetic shield.
3. Results and Discussion

3.1. Shielding property

To evaluate the shielding performance of the magnetic shield, we measured the shielding factor using a fluxgate magnetometer and a Helmholtz coil. The z-axial shielding factor at position \( r \) is defined by \( S_z(r) = 20 \log \left| B_0 / B_z(r) \right| \) (dB), where \( B_0 \) is the magnitude of an external magnetic field parallel to the z-axis and \( B_z(r) \) is the z-axial magnetic field at position \( r = (x, y, z) \). The distributions for the z-axial shielding factor at 20 Hz are plotted in Figure 3. The inset shows the axes of the coordinates.

Figures 3(a), (b), and (c) plot the shielding factor on the \( x \), \( y \), and \( z \) axes. The shielding factor on the \( x \) axis in a range from \( x = -0.4 \) to 0.4 is from 48 to 50 dB. On the \( y \) axis, it is about 48 dB in a range from \( y = -0.1 \) to 0.1 and gradually decreases as the position approaches the open ends, i.e., \( y = 1 \) and -1, where it is about 20 dB. It is about 48 dB in the vicinity of the center of the \( z \) axis, but it sharply decreases in a range from \( z = 0.4 \) to 0.8 as \( z \) increases because of the upper opening.

According to these results, the distribution of a magnetic field is uniform in the vicinity of the magnetic shield. The uniformity of a magnetic field in a magnetic shield has a great influence on the noise-reduction rate of gradiometers. In this study, z-axial 1st-order gradiometers with a 50-mm baseline were used, so vertical (z-axial) uniformity of a magnetic field in the magnetic shield is required. As we can see from Figure 3(c), the distribution for the shielding factor is uniform in a range from \( z = -0.4 \) to 0.2 due to the auxiliary magnetic shield.

![Figure 3](image)

**Figure 3.** Shielding factors for open magnetic shield on (a) \( x \) axis, (b) \( y \) axis, and (c) \( z \) axis. Inset is a schematic of open magnetic shield and shows axes of coordinates.

3.2. Magnetocardiogram

A magnetocardiogram was measured with 64 gradiometers based on low-\( T_c \) SQUIDs in the open magnetic shield. Figure 4 shows 64 overlapped waveforms at 8 x 8 recording sites on a human chest. The data were acquired at a sampling rate of 1 kHz and passed through 0.1-100-Hz band-pass and notch filters. The data were averaged over 27 times. This demonstrates that the open MCG system we developed clearly detects magnetocardiogram waveforms, including the P-wave peak.

We introduced a current arrow map to visualize the distribution of myocardial ion currents. Current arrow vector \( \mathbf{I} \) can be estimated from the approximation as \( \mathbf{I} \sim (dB/dy, -dB/dy) \). The current-arrow maps are obtained using this simple equation. Figures 5(a), (b), and (c) are respective current-arrow maps of the P wave at 57 ms, QRS complex at 217 ms, and T wave at 512 ms. Each current-arrow map is a typical case of a normal subject [13], and there are no distortions in the current arrows. These results indicate that our open magnetic shield does not have any adverse effects on MCG measurements.
4. Conclusion
We evaluated the performance of an open cylindrical magnetic shield for a magnetocardiograph using 64 low-\textit{T}c SQUIDs so that we could miniaturize an entire magnetocardiograph system. The open magnetic shield had a volume that was less than one-fifth that of a conventional MSR and had a revolving door that provided easy access inside the shield as well as easy operation. Moreover, the cost of the open magnetic shield is expected to be less than half that of a conventional MSR. The shielding factor for our magnetic shield was above 46 dB, and its distribution was uniform in the vicinity of the shield. A magnetocardiogram including the P-wave peak could clearly be measured and the current-arrow maps were also normally obtained. According to these results, the open magnetic shield we developed is reasonable for an MCG system because of its small structure, easy access, and excellent performance.

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