Multichannel SQUID system for measurement of spinal cord evoked magnetic field for supine subjects

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Abstract. A SQUID biomagnetometer system for cervical spinal cord evoked field (SCEF) was developed to investigate a non-invasive diagnosis of function of the spinal cord. The measurement system was characterized by a uniquely shaped cryostat designed for supine subjects. The cryostat has a vertical cylindrical main body whose dimensions are 500 mm in diameter and 940 mm in height and a horizontal protrusion from the side surface with 390 mm of length. The sensor array of 35 LTS-SQUID vector gradiometers directed vertically upward is installed in the end of the protruded part. Subjects lie on a bed in supine position with the head running off the edge of the bed and the back of the neck supported on the upper surface of the protruded part of the cryostat standing beside the bed. This structure readily enables the sensor array to approach close to the neck of the supine subject. The subjects can keep their posture stable during the measurement. We demonstrated the cervical SCEF was successfully detected from a healthy subject who was given electric stimulation to the median nerve at the wrist. The intensity of the evoked magnetic field was 40–70 fT in amplitude. The neural signal propagating along the spinal cord was magnetically observed from the investigation of the transition of the magnetic field distribution.

1. Introduction

We are investigating SQUID application to a non-invasive diagnosis of the function of the cervical spinal cord. In the case of the cervical spinal cord evoked field (SCEF) measurement, the posture of the subject is significant in acquiring a stable and reproducible result. The conventional prostrate-style positioning was suitable for laboratory animals but impractical for a human subject because it was difficult for the subject to keep the prostrate position for a long time throughout the measurement and to suppress involuntary fluctuation of the subject’s body caused by electric stimulation. In contrast to the prostrate position, it was revealed in our investigation that a subject could stably keep the posture and the vibration was easily reduced in supine position or reclining position.

We already reported the development of multichannel SQUID biomagnetometer systems for the SCEF measurements optimized for subjects sitting on a chair in reclining position and successfully observed the SCEF signals induced by the two types of the electric stimulation, which were on the thoracic spinal cord with catheter electrodes[1] and on the median nerve at the wrist with surface electrodes[2].
However, it is sometimes difficult especially for the actual patients with disease on the cervix at hospitals to keep their posture stable, even if they are sitting in reclining position. Therefore, there is a strong demand to examine the SCEF measurement with the subjects lying in supine position.

In this paper, we report the newly developed SCEF measurement system for the supine subject and the preliminary observation of the SCEF signals induced by the peripheral nerve stimulation.

2. Instrumentation

2.1. System configuration

Figure 1 shows the configuration of the measurement system. The configuration is almost the same as the previously developed SQUID system for SCEF measurement[2]. The SQUID sensors installed in the cryostat pick up magnetic field from the subject’s cervical spinal cord. The signals from the SQUIDs are extracted from the cryostat and fed to the electronics in the magnetically shielded room (MSR). The electronics include FLL circuit, analog amplifiers and filters. The signals are digitally recorded after appropriate analog signal processing for visualization of the data and further analysis. The electronics, data acquisition unit, and stimulators are controlled by the control and analysis unit. The table for subjects is made of non-magnetic materials and its height and position are adjustable to fit the cervix to the sensor array. In the following sections, the details of the SQUID sensor array and the cryostat which particularly characterize the developed measurement system are described.

2.2. Sensors and sensor array

The observation area for the cervical SCEF measurement is inevitably narrow because of the small area of a cervix and the number of the sensors to be arranged over the cervix is limited compared to other established biomagnetic measurement such as magnetoencephalography (MEG) or magnetocardiography (MCG). Therefore, vector SQUID gradiometers were applied to extract the magnetic field information from the limited observation area as much as possible.

The vector SQUID gradiometer is composed of one axial-type and two planar-type gradiometric pickup coils orthogonally oriented to one another[3]. The axial-type coil detects...
the magnetic field component radial to the subject’s body surface, and the planar-type coils detect the tangential one. The three pickup coils are made of niobium wire connected to the individual LTS-SQUIDs. The independent three components of the magnetic field are detected at once as a result. The dimension of the sensor was shown in figure 2. The baseline length of the gradiometric pickup coils is 68 mm in consideration of the distance between the sensor array and the cervical spinal cord.

Thirty-five SQUID vector gradiometers are positioned in a quasi $5 \times 7$ matrix like arrangement along a cylindrical surface as shown in figure 3. The curvature radius of the cylindrical surface is 145 mm, which was determined based on the investigation of the neck shape of 27 actual patients of spinal cord disease at Tokyo Medical and Dental University Hospital. The sensor array is assembled in machined glass epoxy blocks pierced with holes to hold the sensors as shown in figure 4. This structure reduces the mechanical distortion of the sensor array and the dislocation of the sensors from the designed values when it is cooled down to the liquid helium temperature.

Direct Offset Integration Technique (DOIT)[4] was adopted as the basis of the flux locked loop (FLL) circuit to linearize the flux-voltage characteristics and to improve the dynamic range of the signals. DOIT-type FLL circuit has relatively simple configuration and is suitable for the multichannel SQUID system. The FLL circuit applied to the system is called a double integrator type[2] with a set of integrator and feedback circuit in addition to the conventional DOIT-type FLL, which is effective to reduce the extramural low band noise at the input of the preamplifier.

The typical noise floor at white region was less than 5 fT/Hz$^{1/2}$. This value includes the noise of the FLL electronics, cryostat and cables.

2.3. Cryostat

The cryostat is made of glass fiber reinforced plastic and has a unique shape optimized for supine subjects. The inside structure and the appearance of the cryostat are shown in figure 5(a) and (b), respectively. It has a cylindrical main body and a protrusion radially sticking out from its side surface. The upper surface of the protruded part is cylindrically curved as well as the sensor array. The sensor array is installed tightly fitting in the protruded part in the vertical orientation as shown in figure 5(c). The cool-to-warm separation at the upper surface is less than 7 mm. Subjects lie on a measurement table with their head running off its edge and their back of the neck supported on the upper surface of the protrusion as shown in figure 1.
The cryostat can hold about 70-liter liquid helium. It was designed in consideration of the internal thermal homogenization. Therefore, the SQUID sensors can keep their superconducting state for more than 5 days without refilling liquid helium, even if the liquid helium level gets lower than the position of the sensors.

In the actual SCEF measurement, *in-situ* X-ray imaging is useful to check the location of the subject’s spine relative to the sensor array when the cervix is positioned on the protrusion. X-ray is horizontally exposed from the opposite side of the protrusion and the imaging plate is set beside the protrusion to receive the X-ray. The wires of the SQUID sensors were arranged in the cryostat along the inner wall so as not to interrupt the path of X-ray.

3. SCEF measurement

3.1. Material and method

For verification of the performance of the developed system, we examined the measurement of the cervical SCEF induced by the electric stimulation on the peripheral nerve. The subject was a healthy male at the age of 23. Informed consent and Ethics Committee approval were obtained. The subject lay on a measurement table in supine position in a two-layer MSR. Figure 6 shows the location of the observation area and how the orientation of the $x$-, $y$-, and $z$-axis was defined. The spinous process C4 of the subject was roughly positioned at the center of the observation area using *in-situ* X-ray imaging. The stimulus was a square pulse current of 6 mA in intensity and of 0.3 ms in duration given to the median nerve at the left wrist. The electric stimulus was repeated 4000 times with a repetition rate of 8 Hz.

A band pass filter of 100–5000 Hz was applied to the SQUID signals at the output of the FLL circuit and then the signals were digitally acquired at 40 kHz of sampling rate. All 4000 responses were averaged for the improvement of S/N ratio. After the digital acquisition, digital low pass filter of 1290 Hz were applied to the averaged data. The data from eight of 105 SQUID sensors were accidentally missing. Therefore, the signals of those eight sensors were interpolated by the
Figure 6. Cervical SCEF measurement of a subject in the supine position. The orientation of $x$, $y$ and $z$-axis corresponds to the axes in figure 2 and figure 4.

Figure 7. The transition of the SCEF distribution between 10.0 ms and 13.5 ms in latency. Plain, dotted and bold lines in the contour maps represent outward, inward and zero magnetic field, respectively. The interval between contour lines is 5 fT. The length of the arrow corresponding to 20 fT is shown in (a). The upper side of each map is the side closer to the head of the subject.

signals of the adjacent sensors.

3.2. Results

The SCEF signals were clearly detected at the cervix with sufficient S/N ratio. The transition of the distribution of the SCEF between 10.0 ms and 13.5 ms in latency is shown in figure 7. The arrow maps and contour maps represent the distribution of the components tangential and radial to the body surface, respectively. Each map is a view from the back of the subject. The large outward component rose in the slightly left side of the observation area between 10.0 ms and 11.0 ms in latency. After 11.0 ms, the zero field line of radial component was turning anticlockwise. The tangential components were oriented in the direction from the area of outward field to the inward. This transition pattern is in good agreement with the previously reported results[2, 5].
4. Discussion
The magnetic field distribution accompanied with the neural signal conduction along the axon shows a traveling quadrupole-like pattern according to the preceding studies[6, 7]. In the case of the SCEF induced by the stimulation on the brachial peripheral nerves, however, the transition pattern was much more complicated than the quadrupole-like pattern as shown in figure 7. One of the reasons for the complexity is the fact that the path for the neural signals from the brachial plexus to the spinal cord is not straight but is divided into several routes. It is suggested that there are two types of the magnetic field components. One is a component propagating along the axon and the other is a non-propagating one[2, 5]. Those two components mix at the cervix and make the transition pattern complicated.

The propagating component is significant for the non-invasive diagnosis of the function of the spinal cord because the local conduction velocity estimated by the behavior of the propagating component provide the effective information for the localization of the conduction block of the spinal cord. The propagating components were found in our result. Between 11.25 ms and 12.25 ms in latency, the inward extremum in z direction was traveling in the observation area along the $y = 40$ toward the head as shown in figure 7(f)–(j). After 12.5 ms in latency, the traveling outward extremum was found as well as the inward extremum. It is assumed that these propagating components are a part of the quadrupole-like pattern and the rest of the quadrupole-like pattern would be hidden behind the non-propagating component in the left side. The conduction velocity estimated by the movement of the outward component after 12.5 ms is 92 m/s. This value is within the normal physiological range. For further analysis, magnetic source analysis must be investigated in order to acquire more precise local conduction velocity.

5. Conclusion
105-ch SQUID biomagnetometer system for the measurement of cervical spinal cord evoked field of the supine subjects was developed for the purpose of the application at hospital. The uniquely designed cryostat enables to fit the sensor array to the cervix of the supine subject from back. The subjects can keep their position stable during the SCEF measurement and the transition of the distribution of the magnetic field evoked by the electric stimulation on the median nerve was successfully observed.

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