35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Spinal Cord Evoked Magnetic Field Measurement Using a Magnetospinography System Equipped with a Cryocooler

Yoshiaki Adachi, *Member, IEEE*, Daisuke Oyama, *Member, IEEE*, Jun Kawai, Shigenori Kawabata, and Gen Uehara, *Member, IEEE*

Abstract— **We have developed a magnetospinography (MSG) system that detects weak magnetic fields associated with spinal cord neural activity using an array of low-temperature superconducting quantum interference device (SQUID)-based magnetic flux sensors. A functional image of the spinal cord can be obtained noninvasively by using this system, and it is effective for precise lesion localization in the diagnosis of spinal cord diseases. The running cost of the developed MSG system mainly depends on liquid helium (LHe) consumption, which is required to maintain the superconducting state of the SQUID sensors. To reduce the LHe consumption, we incorporate a pulse-tube-refrigerator-based cryocooler into the MSG system. Cold gaseous helium is circulated between the cryocooler and the MSG system for cooling the thermal radiation shield of the dewar vessel. Consequently, we achieved a 46% decrease in the LHe consumption rate. Conventional biomagnetic field detection such as magnetoencephalography is often hindered by severe low-frequency band noise from the cryocooler. However, in the case of MSG measurements, such noise can be filtered out because the band of the signal is much higher than that of the cryocooler noise. We demonstrated that the signal-to-noise ratio of the cervical spinal cord evoked magnetic field measurement performed with a working cryocooler is comparable to that of the measurement without a cryocooler.**

I. Introduction

Magnetospinography (MSG) is being developed as a new diagnosis tool for spinal cord degenerative diseases such as myelopathy or disc hernia [1]. Noninvasive functional imaging performed using MSG reveals the transitions in nerve current distribution along the spinal cord and peripheral nerves in the cervix [2] as well as in the lumbar area [3]. A weak magnetic field induced by nerve activity in the spinal cord is detected using an array of low-temperature superconducting quantum interference device (SQUID) magnetic flux sensors. The observed spinal cord magnetic field distribution is analyzed using spatial filter techniques such as sLORETA [4] and the reconstructed nerve current distribution is visualized alongside the anatomical image obtained using magnetic resonance imaging (MRI) or X-ray computerized tomography. So far spinal cord evoked potential (SCEP) measurement using epidural catheter electrodes is applied to obtain functional information about the spinal cord [5]. However, SCEP measurement is an invasive method and needs special surgical skills to insert a catheter into spinal canal. MSG is the only method for noninvasively obtaining functional information about the spinal cord. Therefore, it is expected to become an established medical procedure for precise lesion localization in the diagnosis of spinal-cord-related diseases.

In a practical scenario, the high running cost of the MSG system, which is ascribed mainly to the liquid helium (LHe) consumption required for maintaining the superconducting state of the SQUID sensors, would be a burden on hospitals. For other conventional biomagnetic measurement systems such as the magnetoencephalography (MEG) or magnetocardiography (MCG), the high cost of LHe is often a barrier to the introduction of biomagnetic measurements in hospitals.

In a recent study, we integrated a cryocooler with the MSG system to reduce the LHe consumption. We have already indicated that the radiation shield of the dewar vessel was directly cooled using cold gaseous He from the cryocooler, and that doing so decreased the LHe evaporation rate in the dewar. Furthermore, we did not notice any increase in the noise floor due to the cryocooler [6].

However, thus far, this method has rarely been applied to other biomagnetic measurement systems such as the MEG or MCG systems, although it is commonly used to cool cryomagnets in MRI devices. The band of magnetic noise from a cryocooler, which is one or several hertz, overlaps with the signal band of the MEG and MCG measurements and has a negative influence on the measurement. In contrast to MEG and MCG, the MSG system is compatible with the cryocooler because the MSG signal band is more than 100 Hz and does not overlap with the band of the cryocooler noise.

In this study, we demonstrated that the cervical spinal cord evoked magnetic field was recorded with a sufficient signal-to-noise (S/N) ratio even with the cryocooler beside the MSG system.

II. Instrumentaion

A. MSG System

Figure 1(a) shows the configuration of the MSG system used here. This system was equipped with an array of 40 low-temperature SQUID magnetic flux sensors arranged in an 8 × 5 quasi matrix covering an observation area of 140 mm × 90 mm. The SQUID sensors were of the axial gradiometric

This research was partly supported by the “CLUSTER” project, MEXT, Japan.

Y. Adachi, D. Oyama, J. Kawai, and G. Uehara are with the Applied Electronics Laboratory, Kanazawa Institute of Technology, Kanazawa, Ishikawa, 920-1331, Japan (corresponding author to provide phone: e-mail: adachi.y+ieee@gmail.com).

S. Kawabata is with Section of Orthopaedic and Spinal Surgery, Division of Advanced Therapeutic Sciences, Tokyo and Dental University, Tokyo, 113-8159, Japan.

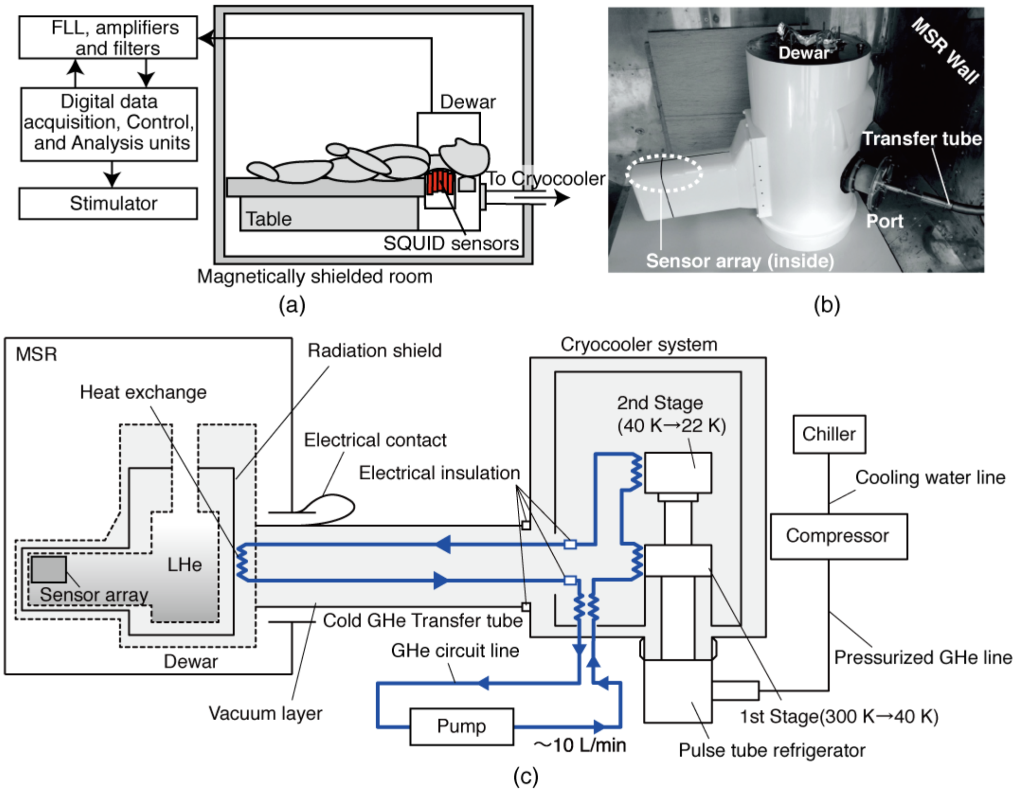

Figure 1(a) Configuration of MSG system, (b) dewar with port for cold GHe transfer tube, and (c) schematic diagram of cryocooler system.

type with a baseline length of 50 mm, driven by double-integrator-type flux-locked loop (FLL) circuits with frequency characteristics similar to those of a band-pass filter of 10 Hz–12 kHz [7].

The dewar was a double-layered vessel made of glass-fiber-reinforced plastic. The dewar's shape was optimized for obtaining measurements from the back of a subject in the supine position. It had a cylindrical main body with a capacity for holding 68 L of LHe and a protrusion from the side surface of the main body [8]. The vertically upward oriented SQUID sensor array was positioned along the upper surface of the protrusion.

Thermal radiation shields made of copper were installed in a vacuum heat insulation layer between the dewar's two plastic layers to create a wrapping around its inner shell. The dewar had a port for connecting a transfer tube to transfer cold gaseous He from the cryocooler on the side surface of the main body, as shown in figure 1(b).

B. Cryocooler system

A gaseous helium circuit was placed between the MSG and cryocooler systems, as shown in figure 1(c) [6]. The gas was cooled to 22 K using a pulse tube refrigerator with a cooling power of 0.5 W at 4 K (CryoMini PDX05/CW701; Iwatani Industrial Gases Corp., Japan). The cold gas was passed through the thermally insulated transfer tube, and the cold gas line was tightly attached to the thermal radiation shield of the dewar to enable heat exchange. The gas flow rate was 10 L/min.

While the cryocooler system was working, the temperature of the thermal radiation shield could be maintained below 40 K. Figure 2 shows a comparison between the LHe level transitions recorded both with and without the cryocooler. According to the gradient of the fitted lines, the LHe consumption rate improved by 46% when using the cryocooler. Through this measurement, we obtained a more precise plot than that in the previous study [6] and found that the obtained consumption rates are reproducible.

III. Measurement and Results

All measurements detailed in this section were performed in a magnetically shielded room (MSR) with two mu-metal layers and one radio frequency (RF)-shielding layer (MONOZ; Ohtama Co. LTD., Japan) having a shielding factor of 39 dB@100 Hz. The cryocooler system was placed at a distance of 1.5 m from the MSR. The distance between the sensor array and the cryocooler system was about 2.7 m. A compressor for generating the pulse gas in the refrigerator,

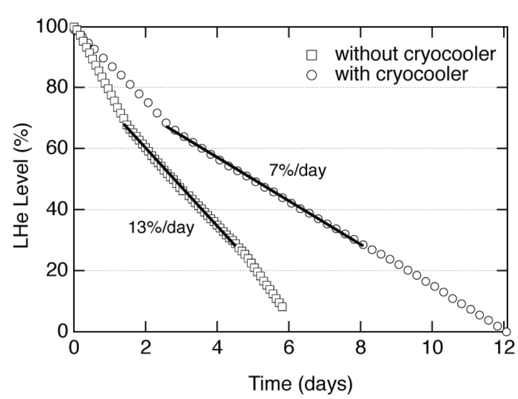

Figure 2 Comparison of transition of LHe consumption rate. The level between 30% and 70% corresponds to the dewar's protruded part.

which was possibly a noise source, was placed at a distance of 6 m from the dewar.

A. System noise

The system noise was recorded while the cryocooler was working and the result was compared with the data obtained before cryocooler installation. All signals from the SQUID sensors were filtered using low-pass filters with a cut-off frequency of 5 kHz and then digitally recorded at a sampling rate of 10 kHz. Figure 3 shows the result of the fast Fourier transform (FFT) analysis of the collected data and its comparison with the data recorded without the cryocooler. In each panel of this figure, the average values recorded from all sensors are plotted.

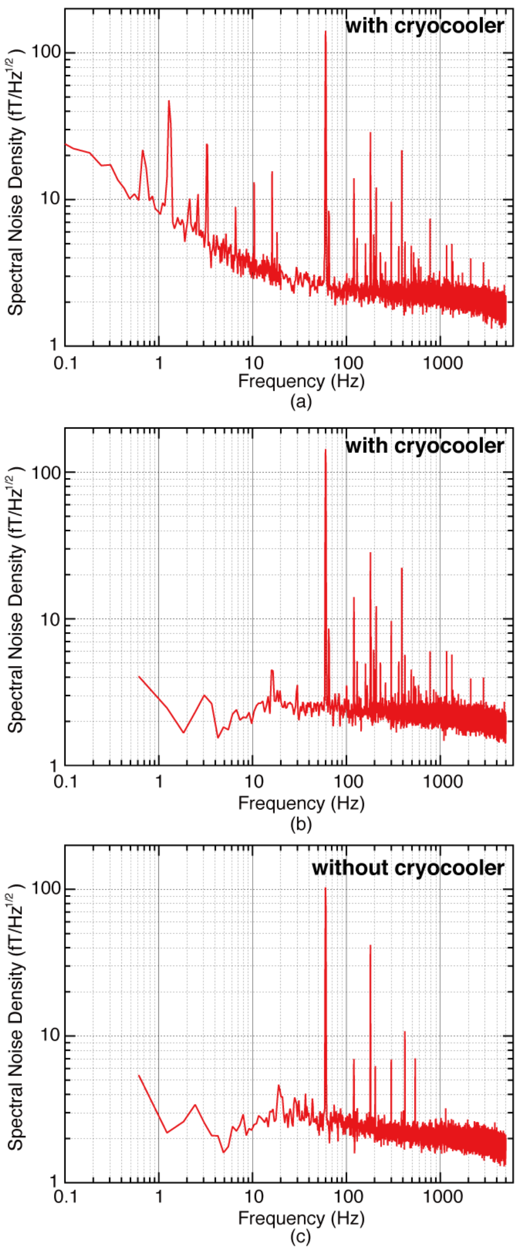

Figure 3(a) Noise characteristics obtained from preliminary measurements in the DC–5 kHz band with the cryocooler, (b) noise characteristics while the double-integrator FLL was active, and (c) noise characteristics obtained without the cryocooler. Panels (b) and (c) are revised from our previous work [6].

In figure 3(a), which is the result of the preliminary noise observation in the DC–5 kHz band, a large peak of height 40 fT/Hz$^{1/2}$ appeared at 1.25 Hz. This frequency corresponded to the frequency of the pulse gas activity in the refrigerator. However, this vibration noise can be reduced effectively using double-integrator-type FLL circuits, as shown in figure 3(b), because the MSG signals' band is more than 100 Hz unlike the bands of other biomagnetic signals such as MEG or MCG.

Figure 3(c) shows the result of the noise measurement without the cryocooler. A comparison of plots in figures 3(a) and (b) with figure 3(c) shows that a noise from the inverter circuit used to drive the valve motor of the pulse tube refrigerator was additionally observed at 65 Hz as well as its harmonics while the cryocooler was working. However, the noise floor remained unchanged before and after cryocooler installation. This indicated that the quality of the data was maintained even when the cryocooler was working beside the MSR. The 65-Hz and harmonics noise should be suppressed by the future improvement of the inverter circuit.

B. Spinal cord evoked magnetic field

To confirm that the noise effect of the cryocooler on the MSG measurement is not substantial, we performed a spinal cord evoked magnetic field measurement for the cervical area while the cryocooler was working. We then compared the result of this measurement with those of the measurement before cryocooler installation. The subject and the conditions, other than cryocooler activity, were identical for the two sets of measurements.

A subject without any spinal cord disease lay on a bed in the supine position with the neck and head running off the edge of the bed as shown in figure 1(a). The neck was in close contact with the top surface of the dewar's protrusion.

The median nerve of the left wrist was stimulated repetitively using a 0.2-ms-long square pulse current of intensity 8 mA. The repetition rate was 8 Hz. A band-pass filter of 100–5000 Hz was applied to each SQUID signal before digital data acquisition. All signals from the 40 SQUIDs were digitized at a sampling rate of 20 kHz. We averaged 4000 epochs to improve the S/N ratio.

Transition of the evoked magnetic field's distribution over the observation area obtained with the cryocooler was compared with the one obtained without the cryocooler, as is shown in figure 4. The zero field line between outward and inward extrema in both transition patterns show an anticlockwise convolution. This pattern transition is in accordance with the result obtained from other subjects using a previously reported MSG system [9]. Figure 5 shows sample waveforms of the detected MSG signals obtained from the sensors positioned along the thin dotted lines shown in figures 4(a) and (f). In both sets of waveforms, the obvious peaks between 10 ms and 15 ms of latency were observed with an adequate S/N ratio. The effectiveness of the additional 65-Hz and harmonics noise were still found but reduced to the acceptable level by averaging. The quality of data obtained when the cryocooler was working was as good as that of the data obtained without the cryocooler.

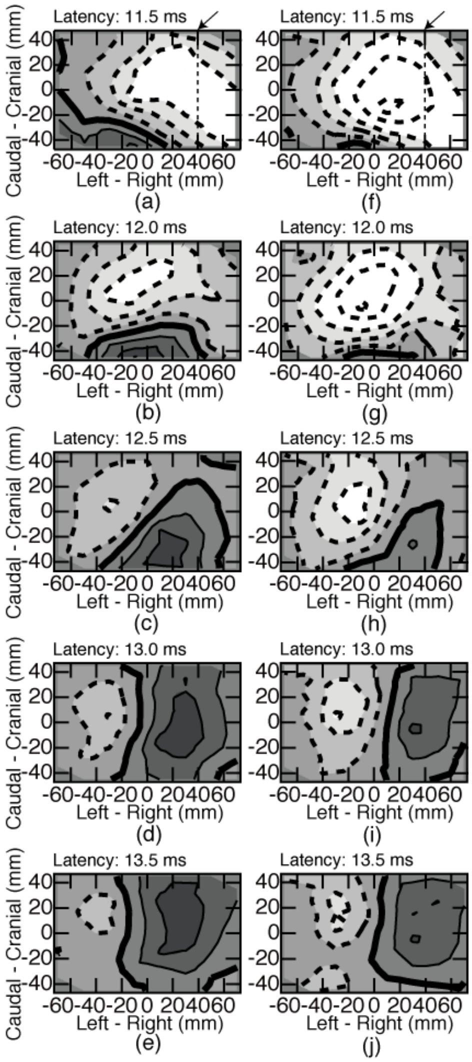

Figure 4(a)–(e) Transition of evoked magnetic field distribution between 11.5 ms and 13.5 ms of latency obtained with the cryocooler; (f)–(j) were obtained without the cryocooler. In each contour map, the plain, dotted, and bold lines represent outward, inward, and zero magnetic fields, respectively, in the radial direction. The interval between the contour lines is 5 fT.

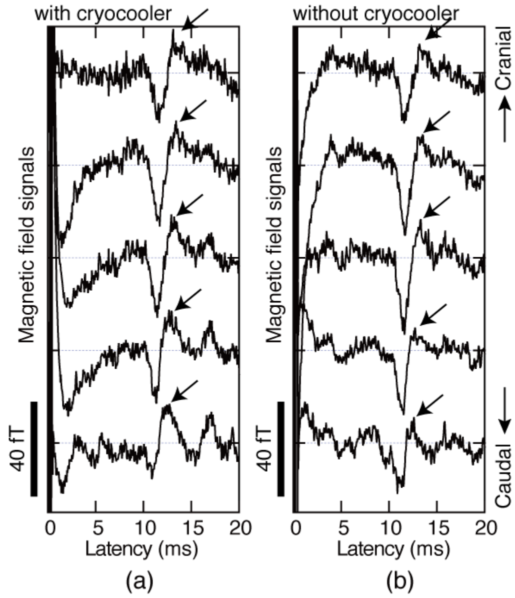

Figure 5(a) Waveforms of MSG signals obtained from five sensors arranged along thin dotted lines indicated by arrows in figures 5(a) and (f) with the cryocooler and (b) waveforms obtained without the cryocooler. The peaks indicated by the arrows in each waveform correspond to the outward poles ascending toward the head in figure 4.

IV. Conclusion

The LHe consumption of a SQUID MSG system improved by 46% upon direct cooling of the dewar's thermal radiation shield using an integrated cryocooler system.

The noise from the cryocooler system, ascribed to mechanical vibration in the refrigerator, was effectively filtered while preserving the MSG signals' band.

Consequently, the typical transition of the cervical MSG signals induced by median nerve stimulation was observed with an adequate S/N ratio even when the cryocooler system was working beside the magnetically shielded room.

Acknowledgment

We are grateful to Dr. Hisanao Ogata and Mr. Jun-ichi Fujihira for their great efforts and practical suggestions that helped in constructing the cryocooler system.

References

[1] Y. Adachi, D. Oyama, S. Kawabata, K. Sekihara, Y. Haruta, and G. Uehara, "Magnetospinography: instruments and application to functional imaging of spinal cords," *IEICE Trans. Fundamentals/ Commun/Electron/Inf&Syst*, vol. E85, in press, 2013.

[2] T. Sato, Y. Adachi, M. Tomori, S. Ishii, S. Kawabata, and K. Sekihara, "Functional Imaging of Spinal Cord Electrical Activity From Its Evoked Magnetic Field," *IEEE Trans Biomed Eng*, vol. 56, pp. 2452–2460, 2009.

[3] S. Ishii, S. Kawabata, S. Tomizawa, M. Tomori, K. Sakaki, K. Shinomiya, K. Sekihara, T. Sato, Y. Adachi, and A. Okawa, "Conductive neuromagnetic fields in the lumbar spinal canal," *Clin Neurophys*, vol. 123, pp. 1656–1661, 2012.

[4] R.D.Pascual-Marqui, "Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details," *Methods Find Exp Clin Pharmacol.*, vol. 24, pp. 5–12, 2002.

[5] K. Shinomiya, K. Furuya, R. Sato, A. Okamoto, Y. Kurosa, and M. Fuchioka, "Electrophysiologic diagnosis of cervical OPLL myelopathy using evoked spinal cord potentials," *Spine*, vol. 13, pp.1225–1233, 1988.

[6] Y. Adachi, D. Oyama, J. Kawai, H. Ogata, and G. Uehara, "Integration of a cryocooler into a SQUID magnetospinography system for reduction of liquid helium consumption," *Physics Procedia*, vol. 36, pp. 268–273, 2012.

[7] Y. Adachi, J. Kawai, G. Uehara, M. Miyamoto, S. Tomizawa, and S. Kawabata, "A 75-ch Biomagnetometer System for Human Cervical Spinal Cord Evoked Field," *IEEE Trans Appl Supercond*, vol. 17, pp. 3867–3873, 2007.

[8] Y. Adachi, M. Miyamoto, J. Kawai, G. Uehara, H. Ogata, S. Kawabata, K. Sekihara, and H. Kado, "Improvement of SQUID magnetometer system for extending application of spinal cord evoked magnetic field measurement," *IEEE Trans Appl Supercond*, vol. 21, pp. 485–488, 2011.

[9] Y.Adachi, J. Kawai, M. Miyamoto, H. Ogata, M. Tomori, S. Kawabata, T. Sato, and G. Uehara, "A SQUID System for Measurement of Spinal Cord Evoked Field of Supine Subjects," *IEEE Trans Appl Supercond*, vol. 19, pp. 861–866, 2009.