A multi-channel SQUID system for biomagnetic measurements

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Biomagnetic measurement is a promising tool to investigate electrical activities in a living body noninvasively. A weak magnetic field induced from nerves or muscles is detected by highly sensitive magnetic flux sensors, and magnetic source analysis reconstructs the electrophysiological current distribution.

Superconducting quantum interference devices (SQUIDs) are typically applied to the detection of the biomagnetic signals whose intensity is on the order of 10^{-15}–10^{-12} T. The structure of the SQUID is a superconductor ring with a single or two Josephson junctions, consisting of two superconductors sandwiching a thin insulating or normal conducting layer to form a weak link. When a bias current larger than the critical current is applied to the ring, the SQUID induces a voltage (V). The voltage is modulated periodically depending on a magnetic flux (Φ) applied to the SQUID ring. The period is exactly equal to the magnetic flux quantum. This gives a large differential coefficient (dV/dΦ) that contributes to highly sensitive magnetic flux detection. The SQUID is connected to a flux-locked loop (FLL) [1] to linearize its output and improve its dynamic range. The flux quanta counting [2], thanks to the periodic characteristics of the Φ-V curve of the SQUID, also broadens the dynamic range. The SQUID sensors are usually equipped with a superconducting gradiometric pickup coil to cancel external magnetic flux disturbances. These make it possible to detect cardiac biomagnetic fields outside of a magnetically shielded room [3].

We developed a SQUID biomagnetic measurement system intended for the spinal cord, peripheral nerves, and muscles [4]. The system had two main characteristic features. The first one was the sensor array equipped with 44 vector-type gradiometric magnetometers arranged in an area of 110 mm × 160 mm. The vector-type gradiometric magnetometer was composed of one axial-type and two planar-type gradiometric pickup coils combined into a single bobbin. Each pickup coil was coupled with three individual SQUIDs and oriented perpendicular to each other so that three independent components of magnetic fields, not only the radial component but also the components tangential to the body surface, could be detected simultaneously. This is effective to extract the magnetic field information maximally from the narrow observation area, such as a neck or wrist. The second characteristic feature was the uniquely shaped cryostat to keep the SQUID sensors in their superconducting state. The cryostat had a cylindrical main body to reserve liquid helium (LHe) and a protrusion from its side surface. The sensor array was installed along the upper side in the protrusion so that the magnetic field could be detected from the bottom of the target pillowed on the protrusion. The cool-to-warm separation at the sensor array was approximately 10 mm.

Our SQUID system was equipped with closed-cycle helium recondensation using a pulse tube cryocooler [4]. In the past, high operational cost because of the LHe consumption to keep the superconducting state of the sensors prevented conventional SQUID systems from becoming widespread. However, the closed-cycle helium recondensation allowed us to recycle almost 100% of the LHe, so our SQUID system continued to be in operation for more than nine months without refilling the LHe, and the operational cost of the system was drastically reduced.

Using the SQUID system, we had already corrected spinal cords' or peripheral nerves' biomagnetic data from more than one hundred subjects. Neural current distributions were reconstructed from the obtained biomagnetic data using spatial filter analysis. Propagation of the neural signals along spinal cords or peripheral nerves was clearly visualized as a transition of the reconstructed current distribution. It was indicated that clinically significant information can be obtained by our SQUID system [5].

References

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