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Auditory evoked field measurement using magneto-impedance sensors

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The magnetic field of the human brain is extremely weak, and it is mostly measured and monitored in the magnetoencephalography method using superconducting quantum interference devices. In this study, in order to measure the weak magnetic field of the brain, we constructed a Magneto-Impedance sensor (MI sensor) system that can cancel out the background noise without any magnetic shield. Based on our previous studies of brain wave measurements, we used two MI sensors in this system for monitoring both cerebral hemispheres. In this study, we recorded and compared the auditory evoked field signals of the subject, including the N100 (or N1) and the P300 (or P3) brain waves. The results suggest that the MI sensor can be applied to brain activity measurement.
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I. INTRODUCTION

Human brains send and receive millions of signals every second, and those signals make us think and move. Measuring brain activity is an important way to monitor those signals. In medicine, some diseases and injuries, such as neural damage, epilepsy, and tumors, can interrupt normal brain activity, and those diseases and injuries can be diagnosed by analyzing brain signals. Measuring brain activity would also be effective for research into cognitive functions. In engineering applications, brain signal measurement can have applications in robotics. Neuroprosthetics based on brain computer interfacing (BCI) technology could be improved to help disabled people, for example.

Electroencephalography (EEG) and magnetoencephalography (MEG) are the most common techniques for measuring and monitoring brain activity. In the conventional scalp EEG system, brain signals are recorded by electrodes positioned on the scalp with a conductive gel or paste. The number and placement of electrodes are based on measurement objectives and demand for spatial resolution. Furthermore, before measurement, the scalp area needs to be cleaned in order to reduce impedance due to dead skin cells. On the other side, arrays of Superconducting Quantum Interference Devices (SQUIDs) are the most reliable sensitive magnetometer used in MEG measurement. SQUIDs are highly sensitive and accurate. However, to maintain superconductivity, the magnetometer heads need to be cooled in a liquid nitrogen or liquid helium environment during the measurement. And the SQUIDs are usually setup in a magnetically shielded room, which makes the devices inconvenient. Compared to EEG electrodes and SQUIDs, the Magneto-Impedance (MI) sensor used in this study is smaller has a lower power cost, and there is no need for the magnetically shielded room. Furthermore, the measurement can be made at room temperature.

Auditory evoked field (AEF) is a neural activity induced by auditory stimuli and recorded by MEG. The AEF is composed of a series of positive and negative magnetic field deflections which can be distinguished by their relative latency and polarity.[1]

N100 (or N1), one of the most prominent responses in the AEF, surfaces as a negative deflection with a latency of roughly 80–120 ms after the onset of a stimulus. Longer latency responses after 100 ms are referred to as event-related fields (ERF), and P300 (or P3) is a part of ERF. P300 surfaces as a positive deflection with a latency of approximately 250–500 ms after the onset of a stimulus. In the application level, the P300 brain waves have been used in various fields such as lie detection, BCI technology, and cognitive impairment examination.

Using our previously reported work as a basis, in this study we measured and recorded the N100 and P300 brain waves in both hemispheres using two picotesla-scale MI sensors.

II. MATERIALS AND METHODS

A. MI measurement system

The MI sensor used in this system is a highly sensitive magnetometer. Fig. 1(a) shows the measurement system of MI sensors. There are 3 parts of an MI sensor: the sensor head, the measurement circuit, and the analog filter circuit.

The design of the MI sensor head is based on the pulse-current magneto-impedance effect, which originated from the skin effect in FeCoSiB amorphous alloy wires.[2] As shown in Fig. 1(b), one sensor head includes two MI elements and one MI element includes a pick-up coil and an amorphous alloy wire. Of the two MI elements, one is used to measure the total magnetic field (the magnetic field of the brain, plus background magnetic noise), and the other one is used to cancel out the background magnetic noise, such as geomagnetism. The voltage difference between the two MI elements is used as output, and the distance between them is 3 cm.

The measurement and analog filter circuits consist of basic CMOS IC. Fig. 2 shows the schematic diagram of the MI sensor. A square pulse current is created by the pulse

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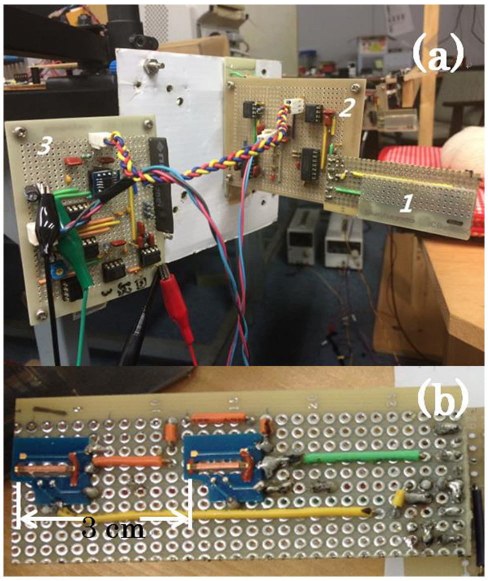

FIG. 1. (a) MI sensor measurement system. (1) MI sensor head. (2) Measurement circuit. (3) Analog filter circuit. (b) MI sensor head without cover.

generator for the skin effect. In the analog filter part, a 60 Hz notch filter is setup to remove commercial power source noise, and a 45 Hz low-pass filter is used to remove high frequency components.

In this study, in order to measure N100 and P300 in both hemispheres, two MI sensors were set on two four-joint support arms, respectively, which can be rotated in 360°.

B. Methods

1. Subjects

Six subjects (four males and two females) were assigned to the N100 task and one subject (female) to the P300 task. All subjects were between the ages of 21 and 29, with normal auditory perception, and no neurological or psychiatric problems reported.

2. Stimuli

The AEF is induced by auditory stimuli, so in this study we used the speaker of a microcontroller to generate the stimuli.

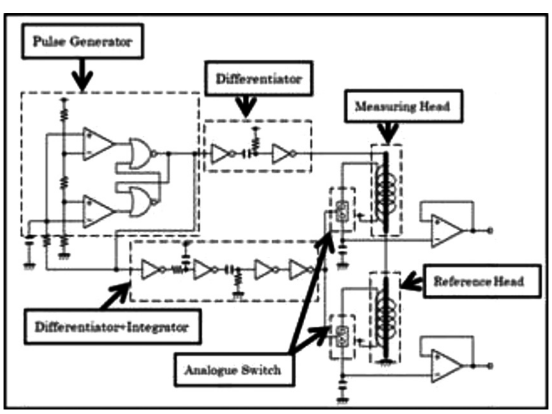

FIG. 2. MI sensor measurement system schematic diagram.

N100: Only one kind of stimulus (1000 Hz) was used in the N100 task. The duration of one stimulus was 200 ms. Interval time between two stimuli was random, from 800 ms to 1200 ms. A total of 500 stimuli (one task with 50 stimuli in total, repeated 10 times) were used on every subject.

P300: Two kinds of stimuli, low probability ($p = 0.2$) target stimuli (2000 Hz) and high probability ($p = 0.8$) standard stimuli (1000 Hz), were used in a random series once every 1500 ms in the P300 task (i.e., the two-stimulus oddball paradigm). The time of one stimulus was 50 ms. A total number of 600 stimuli (one task with 24 standard stimuli and 6 target stimuli, repeated 20 times) were used on the subject.

3. Procedures

N100: The subject laid comfortably on a wooden bed with a relaxed state of mind. Two MI sensors were set above both sides of the temporal region (position T3 and T4 in the international 10–20 system) of the subject for contactless measurement. The distance between the MI sensor head and the scalp was 5 mm. The subject kept his/her eyes open (blinking was acceptable) and heard the stimuli. The sound source was set on the left side of the subject with a 1 m distance.

P300: Different from the N100 task, the two MI sensors were set above the central parietal region (position C3 and C4 in the international 10–20 system) of the subject. The subject laid on the wooden bed and put his/her index finger on a response button. When the task started, the subject was instructed to press the response button to indicate the occurrence of a target stimulus as quickly as possible, but not to indicate for a standard stimulus.[3]

4. Data processing

The output signals of the N100 and the P300 were recorded by a data logger with a 1000 Hz sampling rate. Then, we used a digital filter based on the arithmetic mean and FFT/IFFT to reduce the components of noise and removed the signal components beyond 0.5 Hz–30 Hz. In the N100 task, 500 stimuli conditions were obtained from one subject and we chose 100 conditions with no artifacts for arithmetic averaging. In the P300 task, 120 target stimuli conditions and 480 standard stimuli conditions were obtained from one subject and we chose 100 conditions with no artifacts for arithmetic averaging, respectively.

III. RESULTS

A. N100 measurement

The brain activity waveforms repeated the same measurement three times in one subject, which is displayed in Figs. 3(a) and 3(b). Part (a) is from the contralateral (right side) sensor and (b) is from the ipsilateral (left side) sensor. Both of them were processed in the same fashion. The results show that deflections with a latency of approximately 115 ms can be elicited by stimuli, and the polarity of deflections on the left and right temporal regions are opposite. All three tasks results present common characteristics.

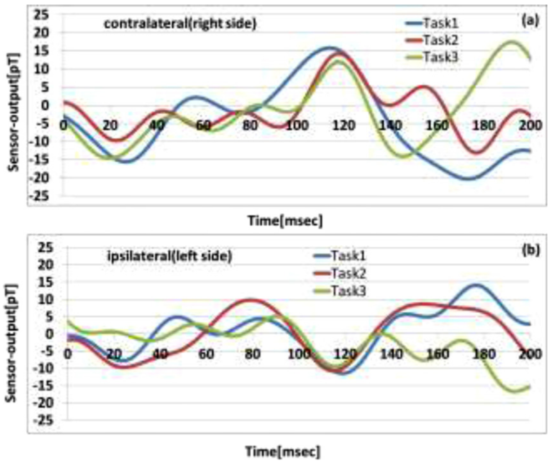

FIG. 3. Mean N100 from contralateral and ipsilateral sensor.

TABLE I. Comparison table of all subjects in N100 and P300 tasks.

Subject	Maximum peak value (pT)	Peak latency time (ms)
(a) N100		
A	17.466	91–113
B	24.392	99–127
C	15.814	108–117
D	17.608	103–112
E	24.94	113–134
F	19.312	107–116
Average value	19.922	103.5–119.8
(b) P300		
A	52.117	345–382
B	79.418	266–369
C	72.331	277–411
D	60.883	364–391
Average value	66.187	313.0–388.3

B. P300 measurement

The brain activity waveforms are displayed in Figs. 4(a) and 4(b). Just as with the N100 data, (a) is from the contralateral (right side) sensor and (b) is from the ipsilateral (left side) sensor, and both target conditions and standard conditions were processed in the same fashion. The results show that positive deflections with a latency of approximately 300–400 ms can be appreciably elicited by target stimuli, but barely elicited by standard stimuli in the left hemisphere, but in the right hemisphere, neither standard nor target stimuli can appreciably elicit the deflection.

IV. DISCUSSION

A. N100 measurement

In the N100 AEF measurement, six subjects performed the task, and the results show similar characteristics. We compared our results with other results of the N100 research,[4,5] which reported the measurement of brain activity via EEG and MEG methods. The waveforms show similar characteristics with our results. In Table I, (a) shows all six subjects' maximum N100 peak values, latency times, and the average value.

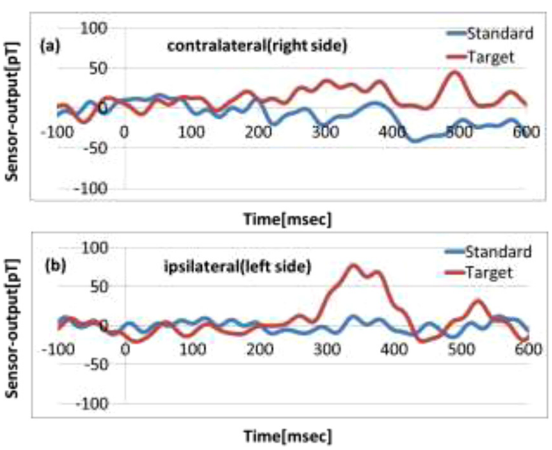

FIG. 4. Mean P300 ERP elicited by target and standard stimuli of oddball paradigm.

B. P300 measurement

In the P300 level, the subject performed the two-stimulus oddball tasks. Compared to our past reported results,[6] Figs. 5(a)–5(c) show the waveforms of the P300 task measured in the parietal region of three other subjects (only one MI sensor was used on position Pz). All of the waveforms show the deflections can be elicited by target stimuli, but not by standard stimuli around 300–450 ms. We also refer to other results of the P300 research[7,8] measured via EEG and MEG methods. These waveforms show similar characteristics to our results, with only a minute difference in amplitude and latency time due to different subject situation. In Table I, (b) shows all subjects' maximum P300 peak values, latency times, and the average value.

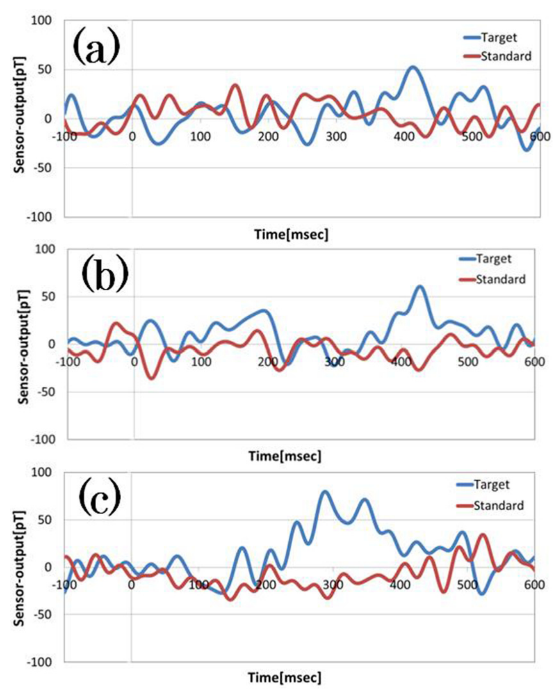

FIG. 5. Mean P300 ERP elicited by target and standard stimuli of oddball paradigm we reported previously.

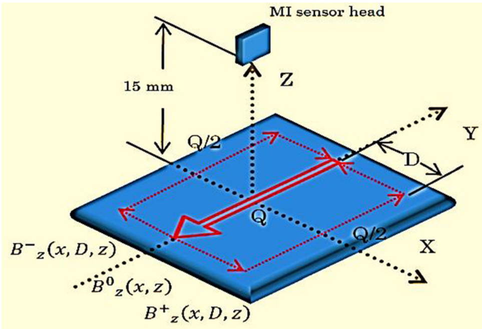

FIG. 6. Sketch of the MI sensor measurement model.

About the waveforms in the right hemisphere, two MI sensors were setup based on the 10–20 system, which only has 21 electrode locations over the whole scalp, and the locations we chose might be a little different due to the subject situation. For MEG measurement, the field direction and amplitude could be changed by even a slight movement (Ref. 9, Fig. 1). We will run more tests in subsequent research to verify our results.

C. The magnitude of the magnetic field

Fig. 6 is the measurement model we reported in past work.[6] In this model, we treat the brain surface locally as a plane. Red arrows represent the current direction (the dashed line means return current). Q is the brain's current dipole source, D is the distance between the current dipole source and the return current, and z is the distance between the cerebral cortex and the MI sensor head. Z direction magnetic field (Bz) along x axis is as follows:

$$B_z(x,D,z) = B^0{}_z(x,z) + B^+{}_z(x,D,z) + B^-{}_z(x,D,z), \quad (1)$$

$$B^0{}_z(x,z) = \frac{\mu_0 Q}{4\pi}\frac{x}{\sqrt{(x^2+z^2)^3}}, \quad (2)$$

$$B^+{}_z(x,D,z) = \frac{\mu_0}{4\pi}\frac{Q}{2}\frac{D-x}{\sqrt{((D-x)^2+z^2)^3}}, \quad (3)$$

$$B^-{}_z(x,D,z) = \frac{\mu_0}{4\pi}\frac{Q}{2}\frac{-D-x}{\sqrt{((D+x)^2+z^2)^3}}. \quad (4)$$

In this formula, μ_0 is the vacuum permeability. Using this model on SQUIDs, where the z is about 60 mm, assuming the Q is 50 nAm for N100 in the temporal region,[10,11] D is 20 mm, and the maximum value of the magnetic field of N100 is estimated as 0.090 pT when x is 10.8 mm (experimental value is about 0.08 pT (Ref. 12)). And on the MI sensor, z is about 15 mm. The maximum value of the magnetic field of the N100 is estimated at 10.858 pT. It is approximately 120 times bigger than the estimated value of SQUIDs.

V. CONCLUSION

In this study, we measured the AEF brain activity in the temporal and the central parietal region using two MI sensors, and after comparing our results with other relevant research, the reliability of our data was confirmed and it suggests that the MI sensor can be used for the measurement of brain activity.

ACKNOWLEDGMENTS

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