Recording the Distribution of Cardiac Magnetic Fields in Unshielded Earth's Field

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***Abstract*—Magnetocardiography (MCG) is a noninvasive technique that allows to measure the cardiac magnetic fields generated by the electrical activity of the heart. Conventionally, the magnetic field distributions around the body surface are recorded by superconducting quantum interference devices (SQUIDs). The SQUID magnetometer usually requires a big cryogenic Dewar vessel and a magnetically shielded room, which makes the SQUID-based MCG system inflexible and expensive. In this paper, we introduce an unshielded MCG system based on optically-pumped magnetometers (OPMs). By operating the magnetometers in a gradiometric mode, together with magnetic-field stabilization methods, the magnetic field noise from surroundings is suppressed and a noise floor of $\sim$10 $\mathrm{fT}/(\mathrm{cm}\cdot\sqrt{\mathrm{Hz}})$ is achieved under a bias field of $\sim 54,500$ nT. With the MCG system, we successfully observe the MCG signal including P-wave, the QRS complex and the T-wave and further measure the MCG signal distribution around the chest in unshielded environment.**

***Index Terms*—Magnetocardiography; unshielded; optically-pumped magnetometer; multi-channel**

I. Introduction

The cardiac function is based on the conduction of electrical signals. The electric signals activate the heart muscle so that blood can be pumped throughout the body. If we place electrodes on the body surface, we can record this cardiac electrical activity. This method is called electrocardiography (ECG), which is commonly used for diagnosing heart diseases. The electrical signals propagating through the heart also generate magnetic fields. These magnetic fields can be detected with high-sensitivity magnetometers placed outside the body. This method is called magnetocardiography (MCG).

MCG is a noninvasive technique allowed to measure the magnetic field signals of the heart. There are some advantages of MCG, compared with the ECG. First, thanks to the constant permeability of the human body, the magnetic signals are barely affected by the inhomogeneous conductivity of bodily tissues, while the ECG signals can be affected [1]. So, the MCG signals have much less attenuation and distortion than ECG signals. Second, MCG are sensitive to tangential and vortex currents, while ECG are more sensitive to radial currents [1]–[3]. So MCG may provide some information on cardiac current that is difficult to obtain by ECG. Furthermore, the MCG sensor doesn't need to contact the skin of patients. It can be very helpful in some cases, such as severe burns patients. Besides, it can detect the activity of fetal hearts [4].

MCG was first demonstrated with pick-up coils [5], and is mainly measured with the superconducting quantum interference device (SQUID) now, because SQUID has a high sensitivity up to fetoTesla. However, SQUID needs the liquid helium to keep the superconductivity, so it usually requires a big cryogenic Dewar vessel to keep the liquid helium. What's more, in order to suppress the environment magnetic field noise, the SQUID system also needs a magnetically shielded room. The room and big Dewar make the SQUID-based MCG system inflexible and expensive. So the conventional MCG systems based on SQUID are not widely used in hospitals. Recently, a highly sensitive room temperature optically pumped magnetometer (OPM) becomes attractive [6]–[8].

Several multichannel MCG systems based on OPMs have been developed in recent years. The most common OPM for detection of MCG signals is spin-exchange relaxation free (SERF) magnetometer. In 2019, the Genetesis company developed a commercial cardiac imaging platform using SERF OPMs and received the FDA clearance [11]. In 2021, X. Ning *et al.* presented a wearable MCG system based on SERF OPMs [12]. The SERF magnetometer has the advantages of high degree of miniaturization and portability. It is one of the most sensitive magnetic sensors. However, the SERF magnetometer still requires a magnetically shielded cylinder [12]–[14], because it must work in a near zero magnetic field [15], [16]. The magnetically shielded cylinder may induce some problems. For example, first, it may induce the claustrophobia. Claustrophobia is the irrational fear of confined spaces, and about 5-10% of the world population is affected by severe claustrophobia. Besides, the magnetically shielded cylinder is made up with soft magnetic materials. Although it is much cheaper and more flexible than the SQUID MCG, it still relative expensive and inflexible, especially comparing with the ECG. In addition, removing the magnetically shielded cylinder is also a possible way to combine stress tests and MCG. A stress test, also called an exercise stress test, shows how the heart works during physical activity. Exercise stress tests can reveal problems with blood flow within your heart, because exercise makes your heart pump harder and faster. If we can git rid of the magnetic shielded cylinder, it is possible to make the patient free of move and make stress MCG test.

Recently, Limes et al. presented an unshielded MCG measurement with OPM sensor last year [17]. They developed a method of measuring the total magnetic field by detecting the free-precession frequency in a highly spin-polarized alkali-metal vapor, and compose two magnetometers to a first-order gradiometer. And they used this gradiometer to measure the magnetic signal of heart and brain successfully.

II. Methods/Results

The OPM used in the unshielded MCG system is based on amplitude-modulated nonlinear magneto-optical rotation (AM-NMOR) scheme, which has been used in the unshielded magnetoencephology system [18]. AM-NMOR magnetometer is different from the SERF magnetometer. SERF magnetometers must work under zero magnetic field, while the AM-NMOR magnetometer can work in a wider magnetic field covering the earth's magnetic field.

The MCG signal strength is sensitive to the distance between the signal sources and the sensors, which makes it possible to suppress the background magnetic noise with gradiometric detection.

We use two AM-NMOR magnetometers to construct a gradiometer, together with feedback methods, to reduce the magnetic field noise. Under the unshielded condition, the atomic magnetic gradiometer has a magnetic field noise floor of $\sim 10\ \mathrm{fT}/(\mathrm{cm}\cdot\sqrt{\mathrm{Hz}})$. This noise floor is good enough for measuring the magnetic signal of heart. The main factor that limited the sensitivity is the nonlinear Zeeman effect.

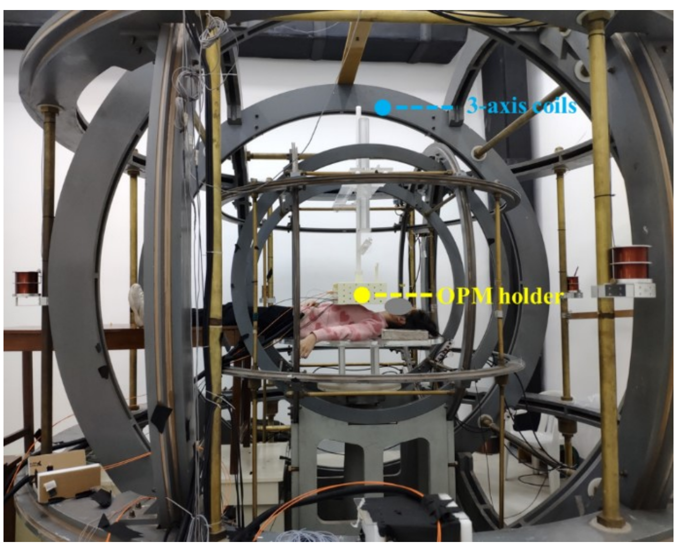

Fig. 1. The overall arrangement of the practical unshielded MCG system.

The overall arrangement of the practical unshielded MCG system is shown in Fig. 1. Two sets of three orthogonal coils are used to adjust the bias magnetic field strength and compensate the field fluctuations. The optically-pumped gradiometer with a baseline of 6 cm is placed in a sensor holder, which can move freely over around above the chest of subjects.

In this work, for heart signals, the sensitivity of $\sim 60\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ is good enough, so we do not need to reduce the nonlinear Zeeman effect. We measured the cardiac signal under the unshielded earth's magnetic field, which is about $54,500\ \mathrm{nT}$ in Beijing. We put the OPM gradiometer above the chest of the subjects, and use feedback methods with the Helmholtz coils to reduce the magnetic noise. The subjects lay on a wooden table with the chest closed to the OPM sensors. We successfully observed the heart signal and can read the QRS waves and T waves clearly.

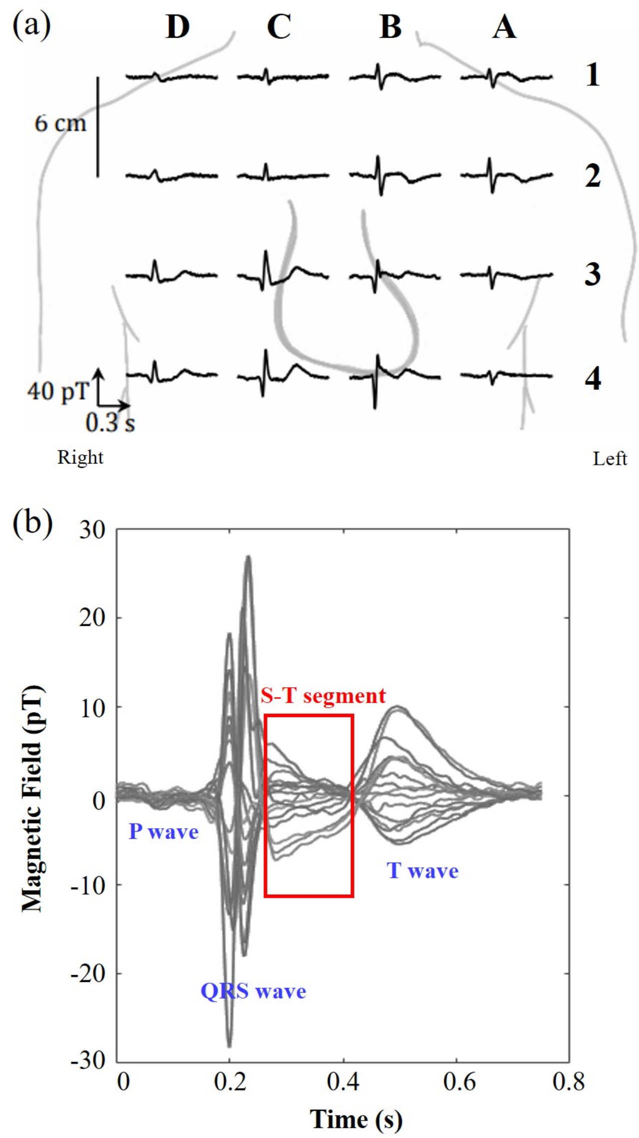

Fig. 2. (a) MCG signals distribution within a cardiac cycle. (b) MCG butterfly diagram.

Then we move the gradiometer to measure 16 locations as a 4×4 matrix. The distance between two adjacent measuring positions is 6 cm. We firstly put the gradiometer at the A1 position, and move the gradiometer in a S-shaped way to measure all the 16 positions. The A1 position is located in the middle of the left clavicle. Figure 2(a) shows all the MCG signals at the 16 spatial positions in a single epoch, which means an unaveraged signal. Because of the difference of distance from heart and electrophysiological activity of heart, the phages and amplitudes of MCG waveform are different with the position.

If we put all the signals measured at different positions in one diagram, we get a MCG butterfly map, as shown in Fig. 2(b). The butterfly map clearly shows the temporal distribution of MCG. These signals are 10 cycles averaged and the P wave can be clearly observed.

III. Discussion

According to Fig. 2(a), we can find that the maximum amplitude of MCG signal is at B4 location. It is on the edge of the matrix, which means that the 4×4 matrix may not cover all the region with MCG information. This shows that the 4×4 matrix is not large enough. Perhaps it is better for a larger matrix to cover more area.

Figure 2(b) shows the MCG butterfly diagram showing an abnormal S-T segment. It may be our subject having some potential abnormalities, or it may also be a character of heart under earth's magnetic field. We are not aware of the reason up to now, and will locate it in the future.

There are also many challenges in developing this unshielded MCG system. The first challenge is to suppress the magnetic field noise, because the magnetic variation can mix with measured MCG signals. A possible solution is to stabilize the magnetic gradient actively, or to develop higher-order magnetic gradiometers. The second challenge is to reduce the size of magnetometer and construct an array, because the current sensor size is relatively large. We will try to use miniaturized vapor cells, to reduce the size of the magnetometer. Another challenge is to reduce the systematic errors caused by body movements, because the signal we measured is the projection of MCG signal along the bias field. We will try to monitor the body movements of the person, and develop the data post-processing methods to reduce the systematic errors. So, to allow multi-sensor recordings and stress MCG test indeed require many significant steps.

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