Innovative Analysis and Application on Magnetograms Signal

Yantong Wang†† and Lingyi Zhou‡‡

†School of Automation, Nanjing Institute of Technology, Nanjing, Jiangsu, 21167, China
‡School of Information Science and Technology, ShanghaiTech University, Shanghai, Pudong District, 201210, China
†Corresponding author's e-mail: x00203191129@njit.edu.cn; zhouly@shanghaitech.edu.cn
‡These authors contributed equally.

Abstract. This study aims to make research on magnetocardiography (magnetograms) signals. Magnetocardiogram is a non-invasive method to record and analyze the magnetic components of the electromagnetic field generated by cardiac electrical activity in the cardiac cycle. We conclude the basic characteristics of the magnetograms signal to summarize the existing magnetograms measurement principles. Then we combine the initial development process and detection means of magnetograms by discussing the signal shielding of magnetograms from two aspects of hardware and software. We compare several methods of shielding electromagnetic signals on hardware and finally obtain an excellent means to shield external signals at this stage. We also conclude the current application of magnetograms in medical treatment.

1. Introduction
The beating of the heart produces weak bioelectrical phenomena that can be recorded on the body's surface by ECG. But it is significantly attenuated by the passage of the signal through the tissues. However, it is very difficult to measure cardiac magnetograms compared to ECG, but the information obtained from cardiac magnetograms has more advantages. For example, it is not affected by tissue or space, and the signals do not decay. It has higher sensitivity and specificity. Magnetocardiogram is a non-invasive method to record and analyze the magnetic components of the electromagnetic field generated by cardiac electrical activity in the cardiac cycle. The cardiac magnetic field is extremely weak, only 10^-10 T (Tesla), while the earth's magnetic field is 10^-4 T (Tesla). Common analysis methods used in clinical research include (1) Magnetic field intensity time spectrum: like electrocardiogram (ECG), it is composed of a group of waves, which are divided into P wave, QRS wave, T wave, and ST segment; (2) Magnetic field distribution map (or isomagnetic field map): using the method similar to mapping, the points with equal magnetic field intensity on the frontal plane can be connected into contour lines, and the isomagnetic map can be obtained by two-dimensional interpolation between the two points; (3) Current density diagram. The electrical activity of the myocardium often reflects the functional state of the myocardium. The magnetic field generated by this electrical activity can penetrate human tissue without signal attenuation during the blood supply, excitability and conduction of the myocardium change, the current and magnetic field in the body will change. MCG detects cardiac electrophysiology through the change of cardiac magnetic field. Hence magnetocardiogram has become one of the newest research hotspots in the field of cardiology and
biomedical engineering. Numbers of studies have shown that magnetocardiogram is instrumental in the diagnosis of coronary heart disease, arrhythmias and other heart diseases and magnetocardiogram devices are constantly being developed. Therefore, a summary of the principles of magnetocardiogram devices, shielding technic and clinical applications of magnetocardiogram in recent years could contribute to improving the shielding techniques of magnetocardiogram devices and exploring possible application scenarios. This paper describes the basic principles and characteristics of magnetograms, introduces the shielding technic, and summarizes some recent data on clinical applications. Basic principles and characteristics of magnetograms

1.1. Detection of magnetograms

From the source of the magnetograms signal and the analysis method can be seen that the magnetograms detection has the following characteristics:

1. The sensor probe of the magneto-cardiogram does not touch the human skin and is far from the power source. The baseline of the magnetograms can be determined as an absolute baseline, while the electrodes of the ECG are in direct contact with the skin.

2. For the ring current and the current with equal size and opposite direction, the electrocardiogram cannot be recorded because the effect of the offset does not show the potential difference. However, the magnetic field is enhanced in these two cases, and there are obvious changes in the magnetograms.

3. Since the magnetic permeability is approximately the same in human tissue as in a vacuum, the effect on the tissue between the sensor and the cardiac current can be negligible.

4. The magnetic field vector can be recorded simultaneously in the same region in three dimensions.

5. By recording the magnetic field in the direction of the chest wall can accurately detect the tangential currents of the chest wall [1, 2].

Early magnetograms are used as an induction coil type magnetometer, and the magnetic flux of the circuit magnetic most meter and material breakage meter, but its sensitivity is too low and is not used. Since the late 1970s, magnetograms have only been widely used due to the development of superconductivity technology after developing a successful low-temperature superconducting quantum interference instrument (SOUID). At present, the main cardiac magnetographs used in clinical applications are the CMI-2409 9-channel magnetograms developed and produced by CardioMas imaging, the magnetograms7 cardiac magnetograph produced by SQUID, the MC-6400 cardiac magnetograph produced by Hitachi High-Technologies in Japan, and the ARCOS-50 cardiac magnetograph produced by AtB in Italy.
The first part is the signal acquisition device (system): The magnetograms capture the weak magnetic field signal through this device. With the current development of low-temperature superconductivity technology, the more common sensor is called superconducting quantum interferometer (SQUID), which uses liquid ammonia cooling (-269 °C) in a low-temperature cage to detect and quantify the very weak cardiomagnetic signal and connects to the signal processing system through a fiber optic cable.

The second part is the signal processing system. It usually consists of a computer with a high configuration by the relevant system software through the system low-pass high-pass, band-pass and other digital filters through the signal acquisition filtering and superposition methods to process and analyze the raw data acquired by the signal. The data can be used to form a cardiac magnetogram in the form of P. ORST wave and magnetic flow density vector map, magnetic gradient map, cardiac magnetic vector map, dipole depth curve, ventricular late magnetic position, cardiac magnetic spectrogram and other mathematical models for clinical analysis.

The third part: The shielded room and examination bed provide an ideal testing environment relatively free of external magnetic field interference [3].

2. The shielding technic improvement

2.1. The basic theory of shielding
At present, the frontier technology of magnetograms measurement is based on Superconducting Quantum Interference Devices, SQUID. It is a magnetic flux sensor that converts magnetic flux into voltage. According to its working mode, it can be divided into dc-SQUID and RF-SQUID. Dc-SQUID operates under DC bias current and contains a superconducting ring with two Josephson junctions. RF-SQUID is an RF superconducting quantum interferometer. Its detector device contains a superconducting ring of Josephson junction and an RF resonator coupled with it [4].

In general, magnetograms signals are extremely weak in comparison with environmental noises. So, reducing the interference of ambient noise on cardiac magnetic signals is a necessary approach. Nowadays, the denoising methods for cardiac magnetic signal processing are mainly divided into hardware and software. In terms of hardware, magnetic shielding room and gradiometer are mainly used.

2.2. Passive electromagnetic shielding room
The passive electromagnetic shielding room is relatively simple, including a six-sided shell, door, window and other general housing elements. It requires strict electromagnetic sealing performance, and all inlet and outlet pipelines are shielded accordingly to block the access of electromagnetic radiation. This kind of shielding room can play a basic shielding effect, but because the cardiac magnetic signal is too weak, the physical shielding effect provided by the shielding room cannot fully meet the clinical requirement. In recent years, the active signal shielding room realized by automatic control has also developed rapidly. An active signal shielding room uses the magnetic field measurement in the shielding room to automatically control the signal for active magnetic field shielding. This strategy of signal shielding using the control principle has a higher effect than passive signal shielding [5].

A large deviation at high frequencies reflecting field leakage is probably due to non—ideal structure and construction of the MSR.

2.3. Digital gradiometer
Another study focus on the performance of digital gradiometer under different measurement conditions: inside the shielded room mentioned above and inside a heavily shielded one. Using the first-order axial gradiometer system described above, background field and magnetograms measurements in a noisy environment with weak shielding are performed.
Figure 2. The background magnetic field spectra of (a) the sensing magnetometer, (b) the reference magnetometer, and (c) the gradiometer in the noisy environment with a light shielding.

Figure 3. The background magnetic field spectra of (a) the sensing magnetometer, (b) the reference magnetometer, and (c) the gradiometer within a well-shielded environment.

The research applied ADF to measurement results obtained a single period magnetogram signal to show the average magnetogram signal. This time by using DWT-based denoising after a linear subtraction, we have got a better SNR in T wave than before. The comparison of the averaged magnetograms data over 30 s is shown in Figure 4.

Figure 4. Averaged MCG signals from the same 30-second record, (a) the result obtained by using DWT denoising after linear regression and (b) the result obtained by using ADF instead of calculating the linear output.
Figure 5. Time-averaged MCG signals after ICA and DWT denoising processes.

Usually, the above second-order gradiometer is used to measure the magnetogram signal in the unshielded environment. However, although the higher-order gradiometer has a superior noise reduction efficiency, it also has a disadvantage in that the gradiometer reduces the magnetograms signal and noise. Therefore, we have to decide the proper order of the gradiometer in consideration of the noise environment where the magnetograms are recorded.

Figure 6. is measured by a second-order gradiometer in (a) shielded and (b) unshielded environments.
The first-order and second-order gradiometers exhibit similar field noise levels in a shielded environment, although the field noise of the first-order gradiometer is slightly less than that of the second-order gradiometer. The field noise of the first-order gradiometer increases about 10 times under a partial shielding environment, while the field noise of the second-step gradiometer corresponds to the change of shielding conditions [6].

Figure 7. Field noise of a first-order gradiometer and second-order gradiometer in (a) shielded and (b) partially shielded environment.

Magnetograms signals in shielded and unshielded environments are also measured, and the signal characteristics are compared. Considering the difference between shielded and unshielded environments, the magnetograms signals measured in shielded and unshielded environments do not differ. Therefore, from the survey results, we can believe that the second-order gradiometer has enough ability to measure magnetograms signals in an unshielded environment.
2.4. Other software approaches

Some other software approaches include Fourier transform filtering, superposed average method and wavelet analysis method. These methods give theoretical support to solve the noise in an unshielded environment and shielded environment.

A work of shielding system reduces the low and the mid-range frequency magnetic field noises by use of two separate sets of coils and their controller systems. Using the designed shielding system, the disturbing magnetic signals of the environment could be attenuated up to 50 dB. So, the magnetic signals down to about 10 pT could be obtained in a noisy laboratory environment. [8]

3. The application of magnetograms

3.1 Myocardial injury

In the past, when 12-way ECG examined the myocardial injury, the typical indicators such as T-wave polarity and ST-segment shift were usually determined by the naked eyes based on experience, and its accuracy was limited by the experience of the diagnostician, which was less accurate and difficult to detect early, especially when all these indicators were difficult to observe. In contrast, magnetograms as a non-contact, non-invasive detection means have more registration points. The modern multiplex has more than 60 superconducting quantum interference devices, has a very high sensitivity, high detection accuracy, can be early detection of myocardial injury, ischemia caused by abnormalities. This could have further guidance on invasive procedures to avoid delays in early diagnosis and treatment. Matthias et al. used spatiotemporal correlation analysis (SCA) to investigate cardiac mapping data of magnetograms [9]. This method uses a 31-channels bio-magnetometer, computing 10 parameters for three-time series of linear correlation coefficients. Series I was the correlation of the signal at the QRS maximum for each single time point. Series II was the correlation of the signal at the T maximum for each single time point, and series III was the correlation of the signal at ST-interval/2 for each single time point.
time point. With 110 patients (mean age 62 years, 76 males) and 72 controls (mean age 58 years, 36 males), SCA parameters could separate the two groups with a sensitivity of 72.6% and a specificity of 64%, but the ECG only had a sensitivity of 68.6% and a specificity of 56% for the infarct signs.

3.2. Coronary heart disease
Exercise electrocardiography (ECG) test is the most common screening test, but lower diagnostic accuracy has been reported, especially in women, in subjects with greater functional impairment or after revascularization procedures.

Yen-Wen Wu et al. assess the diagnostic efficacy of magnetograms in the evaluation of subjects with suspected CAD or CAV. 75 patients with suspected CAD and 26 recipients of orthotopic heart transplantation (OHT) with preserved left ventricular (LV) systolic function (ejection fraction [EF] ≥50%) were enrolled [10]. Magnetograms and coronary angiography were implemented. It was obtained using a 64-channel SQUID system. Using a 64-channels bio-magnetometer to construct the QTc interval maps. As QTc dispersion and smoothness index of QTc (SI-QTc) for ischemia detection and localization. For CAD patients, QTc dispersion and SI-QTc are higher. They found that the repolarization heterogeneity index has superior diagnostic accuracy to T-wave propagation mapping patients with suspected CAD.

Fiona E. Smith et al. simultaneously determined dispersion of ventricular repolarization time from 27 healthy volunteers and 22 cardiac patients in magnetograms and standard ECGs [12]. The result shows that significantly greater differences were obtained in magnetograms, although ECGs could also distinguish these cardiac patients and normal subjects.

Although the effectiveness of magnetograms has been assessed in clinical studies, a larger model is needed, and China did not approve the first homemade cardiac magnetic device until 2019. Meanwhile, because of the need to maintain the superconductivity of SQUID, the cost of magnetograms is still much higher than that of ECG. The signal intensity of magnetograms is much lower than that of the geomagnetic field, and a magnetic shielding chamber is needed to improve the quality of detection so that magnetograms cannot be used at the bedside. ECG is still important in clinical examinations, especially in a test of mobility [11]. However, magnetograms have already demonstrated their significance in detecting cardiovascular disease and may be of greater benefit to mankind in the future.

4. Conclusion
Compared to ECG, magnetograms have more advantages. For example, it is not affected by tissue or space, and the signals do not decay. It has higher sensitivity and specificity. The basic components of the magnetograms instrument are mainly composed of three parts, namely the signal acquisition device, the signal processing system and the shielded room.
Magnetic shielding room and gradiometer are the main approaches to reducing ambient noise interference on cardiac magnetic signals. Background field and magnetogram measurements in a noisy environment can be reduced to a lower level using the first-order axial gradiometer system.

The clinical application of magnetograms is far less than that of ECG, and this situation may be difficult to change shortly. Although magnetograms are not approachable as ECG in clinical diagnostic, they are still a promising tool due to their non-invasive, contactless, and high sensitivity. Meanwhile, for earlier and more accurate detection of cardiovascular disease, considering the potential of magnetograms of providing further information for heart diagnosis, magnetograms may become the main cardiac diagnostic technique of the future.

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