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COMMENTARY

# Clinical Applications of Magnetocardiography in Cardiovascular Medicine: Technological Advances, Challenges, and Future Perspectives

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Recent advancements in medical technology have markedly improved the management and treatment outcomes of cardiovascular diseases (CVD) in China. However, because of widespread unhealthful lifestyle choices, such as smoking and alcohol consumption, the incidence and mortality rates of CVD remain alarmingly high. Early detection and accurate diagnosis are therefore critical to mitigating the health risks associated with CVD. Although traditional diagnostic methods such as electrocardiography (ECG), computed tomography, echocardiography, and cardiac magnetic resonance imaging (MRI) are widely used, they have inherent limitations, including insufficient sensitivity, high costs, radiation exposure, or procedural complexity. Magnetocardiography (MCG), a non-invasive, radiation-free, and highly sensitive diagnostic tool, effectively addresses these limitations. MCG, which has notable advantages in early-stage detection, is increasingly being recognized as an essential diagnostic modality in cardiovascular medicine. Here, we summarize MCG device classification and technological developments, clinical applications in CVD diagnosis, market challenges, and future prospects, and additionally evaluate potential future roles in cardiology.

## Principles of Magnetocardiography

Cardiac activity generates bioelectric signals, which are detectable as potentials on the body surface and have conventionally been recorded by electrocardiography. These cardiac electrical activities produce corresponding magnetic fields, known as magnetocardiographic signals. MCG devices use superconducting quantum interference devices (SQUIDs) as highly sensitive magnetic field sensors to record and visualize the subtle local magnetic fields generated by cardiac electrical activity. Advanced digital signal processing techniques enhance signal-to-noise ratios, thus resulting in high-quality magnetocardiograms. Physicians analyze these parameters to accurately diagnose various cardiac conditions, thereby enabling timely preventive and therapeutic intervention (Figure 1).

## Classification and Technological Developments in MCG Devices

MCG devices are classified primarily into superconducting and non-superconducting types according to their sensor technology. SQUID systems operate at cryogenic temperatures and typically require costly magnetic shielding rooms. They offer exceptional sensitivity and spatial resolution

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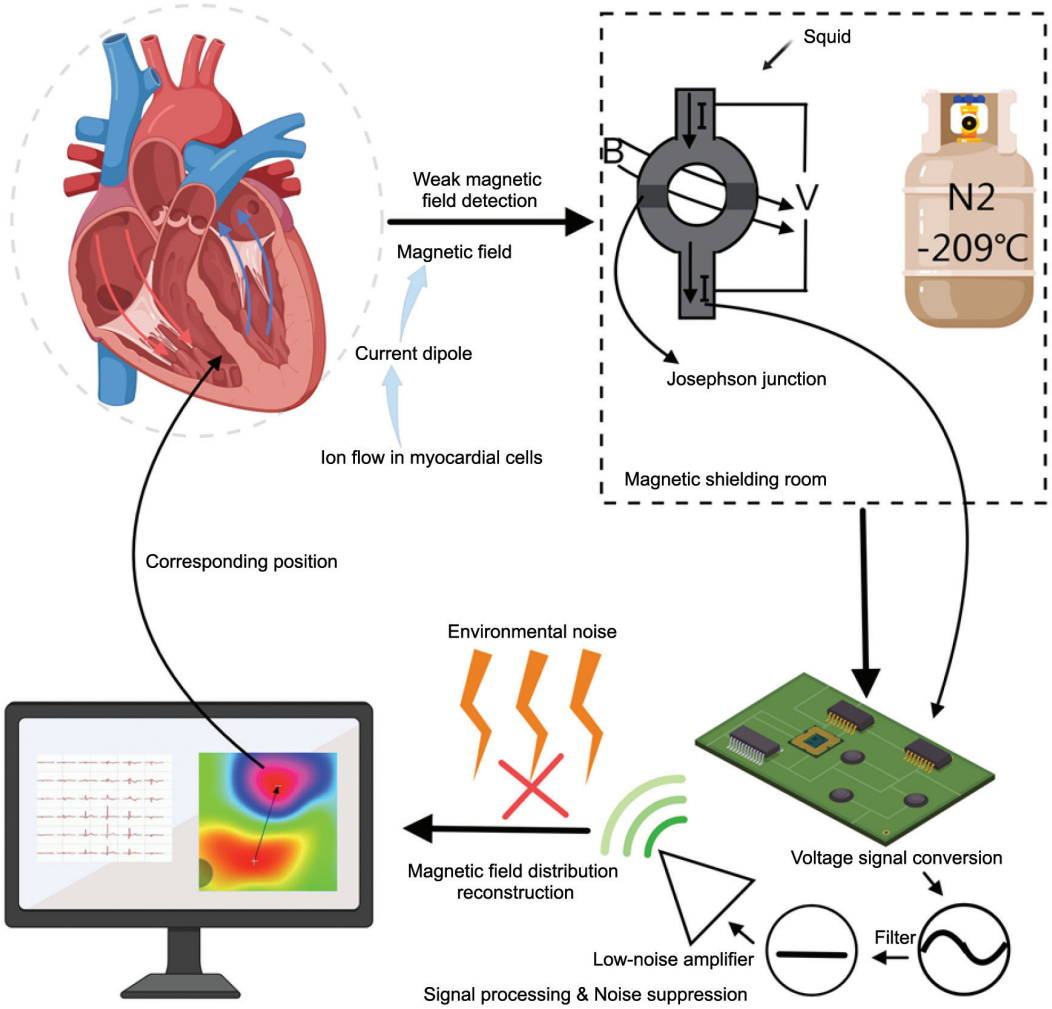


**Figure 1** Schematic Diagram Illustrating the Principle of Magnetocardiography. Created with MedPeer.

but carry high acquisition and maintenance costs. Non-superconducting sensors, such as atomic magnetometers, optical-pumped magnetometers, induction coils, and magnetoresistive sensors, operate at room temperature, and have simpler hardware and lower costs. However, they exhibit relatively lower sensitivity and diminished interference rejection capability. Since its initial demonstration in 1970, MCG technology has undergone substantial advancements across multiple generations (summarized in Supplementary Table 1).

China has also made substantial progress since the development of its first domestic MCG system in 1986 at the University of Science and Technology of China. In 2001, Fuwai Hospital in Beijing introduced advanced foreign MCG technology, which marked the formal inception of domestic research in this field. Nonetheless, the commercialization of MCG in China remains in preliminary stages. The initial development was driven primarily by research institutions and universities, whereas commercial enterprises emerged more recently, after 2018.

## Clinical Applications of Magnetocardiography

Coronary artery disease results from atherosclerotic narrowing that decreases coronary blood flow [1]. Ischemic myocardium shows diminished resting membrane potentials and action potential propagation, thus resulting in heterogeneity in depolarization and repolarization. This heterogeneity generates injury currents at the ischemic and normal tissue, and produces abnormal magnetic fields that can be detected earlier with MCG than ECG [2]. MCG has been applied to early detection of electrophysiological abnormalities associated with ischemia [2], yet the field still lacks standardized diagnostic criteria.

Most studies have analyzed repolarization-phase features, including ST-segment fluctuation scores, T-wave magnetic vector trajectories, T-wave intervals, and ST-interval dipole angles [2]. Recent work has also used machine learning to extract multidimensional spatiotemporal features and build diagnostic models [3].

Numerous clinical studies have reported that MCG's diagnostic sensitivity and specificity are comparable or superior to those of conventional modalities [4]. MCG also supports prognostic and monitoring. Resting-state MCG has been used to predict 3-year mortality in patients with acute chest pain without ST-segment elevation [5]. Newer systems have extended these findings. A prospective optical-pumped magnetometer-based MCG study in borderline (50%–70%) stenoses has achieved an AUC of 0.86, with 79.4% sensitivity and 80.8% specificity, thereby indicating MCG's potential for clinical decision support and functional evaluation [6].

MCG captures subtle atrial activation dynamics in atrial fibrillation (AF) with superior spatial and temporal resolution. Frequently analyzed parameters include P-wave duration, dispersion, and amplitude. In a retrospective cohort of 71 patients, Guida et al. have combined MCG with an equivalent magnetic dipole (EMD) model and achieved 81.5% accuracy in detecting AF [7]. Even during sinus rhythm, patients with paroxysmal AF showed fragmented atrial repolarization magnetic fields that were detectable with MCG. Beyond diagnosis, MCG can be used to noninvasively visualize abnormal reentrant sources to assist ablation, and to depict magnetic dipole trajectories consistent with invasive electrophysiological mapping [8].

In ventricular arrhythmias, MCG not only accurately localizes the ectopic origin but also quantitatively characterizes the conduction abnormalities and electrophysiological substrate, thereby informing risk stratification for malignant arrhythmias such as ventricular fibrillation [9]. In fetal arrhythmias, fECG and Doppler echocardiography lack electrophysiologic detail. However, fMCG can separate fetal from maternal magnetic signals and enable real-time monitoring. Numerous studies have validated its diagnostic value for fetal arrhythmias, including tachyarrhythmias, conduction block, and congenital long-QT syndrome [10]. MCG has diagnostic and monitoring value across cardiomyopathies. In a prospective cohort study of inflammatory cardiomyopathies, an MCG vector threshold of >0.051 separated most cases from controls (specificity 0.95; sensitivity 0.59), and vector values fell within 1 week of immunosuppression, preceding LVEF changes [11]. Case reports and an amyloidosis series have corroborated therapy tracking [12]. In dilated cardiomyopathy, MCG can detect abnormal ventricular repolarization resulting from myocardial fibrosis and remodeling. Among patients with dilated cardiomyopathy, prolonged terminal T-wave indices are associated with malignant ventricular arrhythmias and support risk stratification [12]. In left ventricular hypertrophy, the QRS–T integral is elevated and correlates with left ventricular mass index ($r = 0.455$, $P = 0.002$), with accuracy comparable to that of the Cornell voltage-duration product [13]. Thus, MCG complements echocardiography and ECG by adding electrophysiologic phenotyping and early response signals.

## Market Challenges and Future Prospects

Despite the rising incidence of CVDs and the increasing demand for early diagnosis, clinical use of MCG remains limited. The five major barriers to MCG use are as follows. First, SQUID systems require cryogenics and magnetic shielding rooms, thus necessitating multi-million-dollar outlays and trained maintenance. Access is therefore concentrated in research institutions and tertiary hospitals. Second, ECG, echocardiography, computed tomography, and MRI are first-line modalities in most pathways. Routine adoption of MCG would require demonstration of explicit benefit in defined clinical scenarios, large prospective validation studies, and guideline endorsement. Beyond costs and clinical alternatives, the absence of harmonized operating protocols and unified data formats limits comparability and integration, thus hindering authoritative reference ranges from being determined and large multicenter databases from being constructed. Moreover, clinical awareness is low, because targeted training on biomagnetic diagnostics and interpreting magnetic field maps is scarce. Finally, the technology maturity is uneven. Whereas performance is robust in shielded laboratories, stability

and noise tolerance in ordinary rooms still require validation [14]. Current evidence has focused on coronary artery disease and arrhythmias, whereas data remain limited for heart failure, valvular disease, and other cardiac conditions.

Advances in magnetic sensors, active shielding, and noise suppression are pushing MCG systems toward portability. Deep learning coupled with multimodal integration, such as MCG-MRI fusion and magnetic ion imaging, is driving automated diagnosis and more comprehensive assessment in patients with CVD. AI models using MCG data have achieved sensitivity and specificity exceeding 80% in identifying ischemic heart disease [15]. Additionally, to resolve standardization gaps, the immediate priority is to reach international consensus regarding acquisition workflows, reporting templates, quality-control standards, and related specifications. In parallel, existing datasets should be converted into a common format, integrated, and made openly available [14]. A global, open MCG data repository should then be established to accelerate AI development, enable multicenter studies, and consequently refine standardization. Finally, developing targeted curricula, advancing interdisciplinary medical–engineering training, and establishing a standardized training and certification system would promote broader clinical use of MCG.

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## Conflict of Interest

The authors declare that they have no conflicts of interest.

## Supplementary Material

Supplementary material for this paper can be found at the following link https://cvia-journal.org/wp-content/uploads/2026/01/Supplementary_Table1.pdf.

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