Magnetocardiography Imaging Based on Epicardial Sources for Mapping the Drivers of Atrial Fibrillation

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Abstract

Magnetocardiographic Imaging (MCGI) offers three-dimensional cardiac activation information beyond epicardial electrical activity, making it a valuable complement to Electrocardiographic Imaging (ECGI). This study explores the application of MCGI based on epicardial sources for localizing atrial fibrillation (AF) drivers. Data from six AF patients who underwent radiofrequency ablation with the Carto system were analyzed. Pulmonary vein isolation was performed during the procedure, resulting in AF termination and restoration of sinus rhythm. Preoperative MCGI reconstructions of epicardial magnetic field activity were processed to generate dominant frequency and entropy maps. These maps revealed abnormalities around the left and right pulmonary veins, aligning with the clinical hypothesis that pulmonary veins are common AF driver sites and consistent with intracardiac catheter mapping results. The findings suggest that MCGI with an epicardial magnetic field source has the potential as a non-invasive tool for mapping potential AF drivers, warranting further investigation into its clinical application.

1. Introduction

Non-invasive, non-contact, and radiation-free body surface Magnetocardiography (MCG) is capable of accurately capturing the characteristics of the cardiac magnetic field without signal attenuation [1]. It exhibits greater sensitivity to temporal and spatial variances in cardiac electromagnetic behavior compared to conventional ECG signals. Thus, research into MCG Imaging (MCGI) holds the theoretical potential to reverse-reconstruct the electromagnetic activity of epicardial sources with higher spatial resolution.

The MCGI provides three-dimensional cardiac activation information beyond epicardial electrical activity, complementing ECGI in epicardial potential mapping [2]. Numerous studies have investigated the application of MCGI in localizing potential atrial fibrillation (AF) drivers. In solving the MCGI inverse problem, the heart is commonly modeled as a dipole source or a distributed source [3]. By measuring the magnetic field distribution on the body surface, the position, orientation, or dipole moment of the dipole or distributed source can be determined. Guida et al. utilized MCGI with a magnetic dipole model of the heart, obtaining valuable information for the rapid assessment of AF onset and recurrence risk. Additionally, they successfully reconstructed the trajectory of atrial depolarization through inverse problem solving in MCGI [4]. Sato et al., in a follow-up study of 71 AF patients who underwent pulmonary vein isolation, identified right atrial magnetic field strength as a strong predictor of AF recurrence [5]. Doosang et al. applied data from eight chronic AF patients, and by inverse-solving the f-waves caused by reentrant excitation, they remapped the results onto a three-dimensional cardiac mesh model, visualizing the corresponding current source distribution on the atrial surface. This visualization informed radiofrequency ablation procedures in three patients, successfully restoring sinus rhythm from AF [6]. Fenici et al. emphasized that MCG-based dynamic imaging of atrial arrhythmias could be used to classify AF patients before ablation and to plan more appropriate treatment strategies. However, MCG still requires the development of software tools for automated or interactive three-dimensional imaging, as well as tools for multimodal data fusion comparable to those available in invasive three-dimensional electroanatomical mapping systems [7].

Currently, clinicians rely heavily on invasive endocardial three-dimensional electroanatomical mapping systems to identify potential AF drivers. Compared to dipole and distributed source models, MCGI based on epicardial sources offers anatomical localization of potential AF drivers on the atrial chamber, which facilitates integration with existing endocardial electroanatomical systems. This integration enables fusion of endocardial and epicardial information, advancing the non-invasive mapping of potential AF

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drivers using MCGI.

No previous studies have treated the heart as an epicardial source in solving the MCG inverse problem. This study aims to evaluate the reliability of MCGI in mapping potential AF drivers.

2. Methods

Similar to ECGI [8], according to the Biot-Savart law and Maxwell's equations, the solution to the inverse problem in MCGI can be described as a process of reconstructing the cardiac magnetic field sources from the magnetic field measured on the body surface. Specifically, the magnetic field generated by cardiac electrical activity is modeled, and by solving the inverse problem, the spatial distribution of the underlying epicardial current sources is estimated. The inverse problem in MCGI can be described as

$$X = L^{-1}B$$

Among them, B is the measured magnetic field, L is the forward conduction field matrix, and X is the epicardial source to be reconstructed.

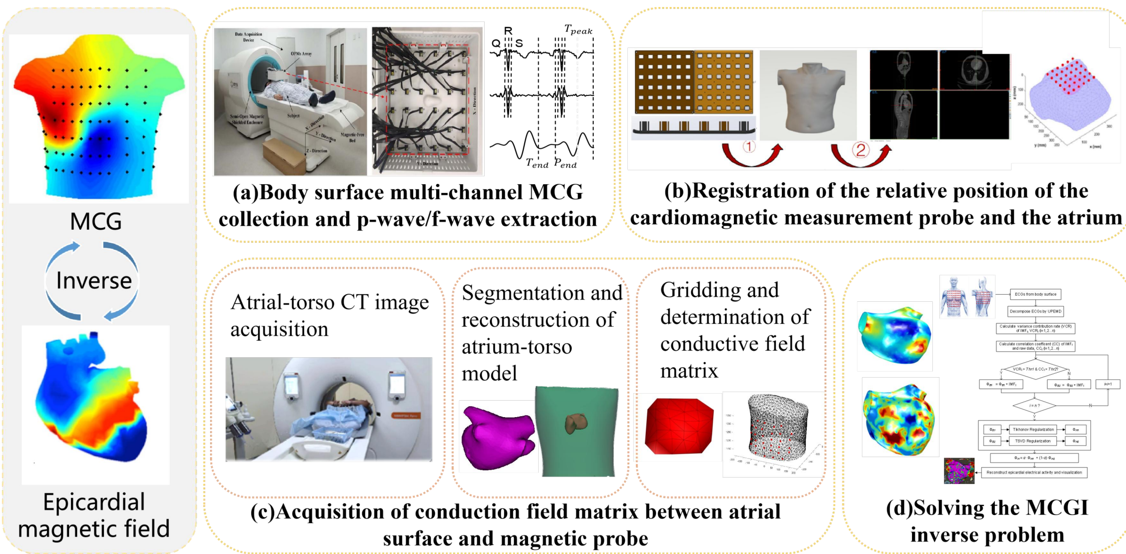

Fig.1. The whole research flow. (a) MCG collection and p-wave/f-wave extraction. (b) Registration of the relative position of the cardiomagnetic measurement probe and the atrium. (c) Acquisition of conduction field matrix. (d) Solving the MCGI inverse problem.

The research methodology of this study is illustrated in Fig.1. Initially, multi-channel MCG signals are gathered, and atrial characteristic waves (such as P waves and f waves) are isolated as the measured magnetic field B. Next, the spatial relationship between the atria and cardiac magnetic measurement probes is established, and the atrium-probe conduction field matrix L is generated using the boundary element algorithm. Subsequently, the ill-conditioned inverse problem is addressed through a multi-scale time-frequency domain regularization scheme. Lastly, post-processing of the epicardial magnetic field activity X is conducted to generate the dominant frequency (DF) and entropy map [9].

A. Multi-channel MCG Signal Processing and Atrial Feature Wave Extraction

Considering the similarity in time-frequency characteristics between MCG and ECG signals, this project intends to combine uniform phase empirical mode decomposition (UPEMD) and hierarchical slope thresholding methods to exclude ventricular activity and extract atrial feature waves. The main implementation steps are as follows:

① Perform time-frequency decomposition of multi-channel MCG signals using the UPEMD algorithm. The final number of decomposition layers will be designed based on the sampling frequency of the MCG and the main frequency distribution of the atrial feature waves.

② After decomposing the signals into intrinsic mode functions (IMFs), select different IMFs for superposition based on their frequency distribution. This includes marking the IMFs for QRS wave detection and the IMFs for T wave detection.

③ Use the slope method to identify the QRS wave. The first local minimum after the first maximum following the S wave will be marked as the T wave endpoint, and the first local minimum before the Q point will be marked as the P wave endpoint. The signal between the T wave endpoint and P wave endpoint will be considered the P/f wave.

B. Calculation of the Magnetic Conduction Relationship (Lead Field Matrix Calculation)

The following steps will be taken to calculate the lead field matrix between the atria and the probes:

① Obtain enhanced CT imaging data of the patient's heart and torso.

② Use Mimics software to segment, reconstruct, and perform adaptive meshing on the CT images.

③ Register the relative position of the probe on the torso to determine its position relative to the atria.

④ Use the boundary element method to calculate the lead field matrix between the meshed atria and the probe.

C. The Solution to the Inverse Problem

The MCGI inverse problem will be addressed using a multi-scale regularization approach based on UPEMD. In this method, the atrial characteristic frequency components are first separated from the remaining signal based on the sampling frequency and spectral distribution of the MCG data. Tikhonov regularization is applied to the primary atrial frequency components, while truncated singular value decomposition regularization is applied to the residual components. The final solution is obtained by taking the weighted average of the regularized results from both components. For a detailed explanation of this method, , refer to the literatures [10,11].

3. Results

In this study, data were collected from six AF cases that underwent radiofrequency ablation using the Johnson & Johnson Carto system. After performing pulmonary vein isolation during the procedure, AF was terminated in these six cases, and normal sinus rhythm was restored. Preoperatively, the MCGI technique based on epicardial sources was used to reconstruct epicardial magnetic field activity. Post-processing of the epicardial magnetic field data yielded DF and entropy maps (Fig.2). Abnormalities were clearly observed around the left and right pulmonary veins on these maps, which align with the clinical hypothesis that pulmonary veins are common sites of potential AF drivers, as well as the intracardiac catheter mapping results during the procedure, which indicated a pulmonary vein origin for AF. These findings provide preliminary evidence of the potential utility of MCGI based on epicardial sources in the mapping of potential AF drivers.

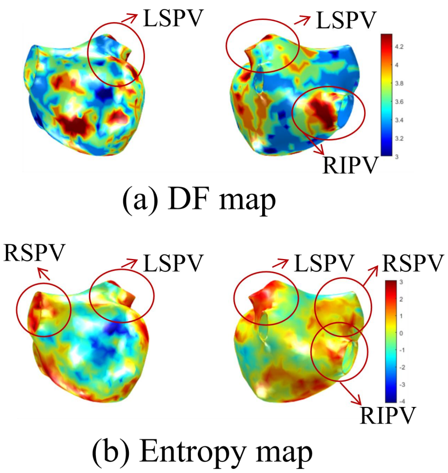

Fig 2. Mapping potential AF drivers via MCGI. (a) the DF map, (b) is the entropy map. LSPV:Left Superior Pulmonary Vein, RSPV:Right Superior Pulmonary Vein, RIPV:Right Inferior Pulmonary Vein.

4. Discussion

The findings of this study highlight the potential of MCGI based on epicardial sources for identifying potential AF drivers. The successful reconstruction of epicardial magnetic field activity provided significant insights into the electrophysiological landscape of the heart, particularly around the pulmonary veins, which are known hotspots for AF initiation and maintenance.

However, it is important to note that this research is primarily an exploratory study. The limited number of cases analyzed may not fully capture the complexity of AF dynamics, and the experimental protocols require further refinement. While the observed abnormalities in the DF and entropy maps correlate with existing clinical hypotheses, larger studies are needed to validate these findings and assess the robustness of MCGI in different AF subtypes.

Future investigations will aim to expand the cohort size and enhance the experimental design to yield more comprehensive insights. By continuing to explore this avenue, we hope to contribute new perspectives to the field and provide valuable information to our peers in the ongoing quest to understand and manage AF effectively.

5. Conclusion

MCGI technology based on epicardial epicardial magnetic field sources has demonstrated the potential to localize potential AF drivers to some extent. Its clinical application warrants further exploration and investigation.

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