

Phantom Validation of Multichannel Magnetocardiography Source Localization

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FENICI, R., ET AL.: Phantom Validation of Multichannel Magnetocardiography Source Localization. *Multichannel magnetocardiography (MMCG) is used clinically for noninvasive localization of the site of origin of cardiac arrhythmias. However, its accuracy in unshielded environments is still unknown. The aim of this study was to test the accuracy of three-dimensional localization of intracardiac sources by means of MMCG in an unshielded catheterization laboratory using a saline-filled phantom, together with a nonmagnetic catheter designed for multiple monophasic action potential recordings in a clinical setting. A nine-channel direct current superconducting quantum interference device (DC-SQUID) system (sensitivity $fT/Hz^{0.5}$) was used for MMCG from 36 points in a measuring area of 20×20 cm. The artificial sources to be localized were dipoles embedded in the distal end of the catheter, placed 12 cm below the sensor's plane. Equivalent current dipoles, effective magnetic dipoles, and distributed currents models were used for the inverse solution. The localization error was estimated as the three-dimensional difference between the physical position of the tip of the catheter and the three-dimensional localization of the dipoles derived by means of the inverse solution calculated from MMCG data. The reproducibility was tested by repeating the MMCG after repositioning the phantom and the measurement system. The average location error of the catheter dipole was 9 ± 4 mm and was due primarily to imprecise depth estimation. Localization was reproducible within 0.73 mm. The distributed currents model provided an accurate image of current distribution centered over the catheter tip. The authors conclude that MMCG estimation is accurate enough to guarantee proper localization of cardiac dipolar sources even in an unshielded clinical electrophysiological laboratory. (PAGE 2003; 26[Pt. II]:426-430)*

multichannel magnetocardiography, cardiac source localization, phantom, nonmagnetic catheter, arrhythmias

Introduction

Previous investigations have demonstrated that multichannel magnetocardiography (MMCG) can be used for noninvasive functional cardiac imaging and three-dimensional localization of arrhythmias, and the number of hospitals in which MMCG devices are installed is increasing.¹⁻¹¹ Until recently, most MMCG systems were reliable only in magnetically shielded rooms (MSRs), and there was great skepticism about the practical clinical usefulness of MMCG (i.e., at a patient's bedside). Indeed, a MSR is expensive, which has limited the widespread clinical application of MMCG, especially with critical cardiac patients, not to mention its potential use for real-time nonfluoroscopic electroanatomic imaging in the invasive

cardiac electrophysiological laboratory. With this in mind, the authors have developed a MMCG system that can be used in an unshielded laboratory fully equipped with electromagnetically "noisy" instrumentation for invasive cardiac electrophysiological and emergency care (Fig. 1A). The clinical reliability of this system is under evaluation.¹²

The aim of this study was to evaluate the accuracy of three-dimensional source localization achievable with MMCG in an unshielded laboratory, using a simple phantom and the same nonmagnetic catheter technique used previously in a MSR in Helsinki.¹³⁻¹⁶

Methods

MMCG Mapping System

The multichannel BioMag system (CardioMag Imaging Inc, Schenectady, NY, USA) installed in the unshielded electrophysiological laboratory of the Catholic University of Rome (Fig. 1A) features nine direct current superconducting quantum interference device (DC-SQUID) sensors, coupled to second-order axial gradiometers with a 55-mm baseline enclosed in a cylindrical cryostat small

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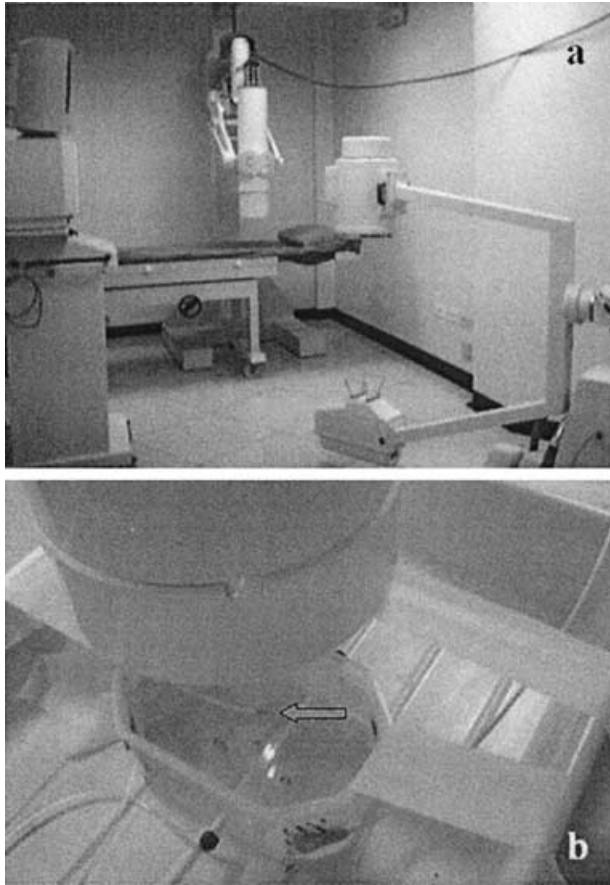


Figure 1. (A) An overview of the unshielded biomagnetism laboratory at the Catholic University of Rome and (B) of the experimental setup. In Panel B, the gray arrow indicates the distal end of the catheter, and the light spot of the laser beam is also visible.

enough to avoid interfering with the operational capability of the cardiologist during invasive electrophysiological interventions. The intrinsic sensitivity of the system is about $20 \text{ fT/Hz}^{0.5}$ in the frequency range of interest for clinical application (1–100 Hz). Signals are recorded with an acquisition system (24-bit analog to digital conversion, 1–2 kHz sampling frequency, and automatic electronic noise rejection) based on the Microsoft Windows NT operating system (Microsoft Corp., Redmond, WA, USA). MCG mapping data were recorded from a 36-point (6×6) grid, covering an area of $20 \times 20 \text{ cm}$, with four data-acquisition sequences. For the inverse solution and source localization, three mathematical models were used: the effective magnetic dipole (EMD) in a semiinfinite space, the equivalent current dipole (ECD) in a realistic torso, and the distributed currents imaging (DCI) model.^{17,18} All inverse computations were performed from averaged MMCG data

after adaptive digital filtering of 50-Hz interference. The localization error was calculated as three-dimensional differences between the MMCG localization and the physical locations (95 or 120 mm in depth, and different positions along the X-Y plane) of the catheter tip. Signal-to-noise ratio (SNR) and goodness of fit (GOF) to the model were calculated for each localization.

Experimental Instrumentation

The phantom was a simple $50 \times 60\text{-cm}$ rectangular tank filled with 0.9% saline solution, simulating a semiinfinite space of homogeneous conductivity 0.21 S/m.

The nonmagnetic catheter used as an artificial source has been described in detail.^{19,20} Briefly, it features multiple electrodes for clinical recording of multiple monophasic action potentials, pacing, and, at the same time, generation of electromagnetic dipoles adequate for MMCG source localization (current 10 mA, duration 2–10 ms, variable pulse rate, usually 100 pulses/min). The distal terminal of the nonmagnetic catheter was attached to a plastic support at the center of the phantom. The support was initially positioned exactly at the center of the 36-point recording grid, then moved slightly along the X-Y plane (Figs. 2 and 3). The sensor plane was 95 or 120 mm from the catheter source.

The Dewar vessel containing the sensors was fixed in the X-Y plane, but movable along Z (height) axis. The sequential positioning of the phantom under the Dewar vessel was done with the same bed used for patient recording, which provides manual control of movements in the X-Y plane with precision on the order of 1 mm. The positioning was controlled with the aid of a laser pointer affixed to the Dewar vessel (Fig. 1B) and a specially designed grid placed on the phantom.

Fifty MMCG recordings were made in ten different sessions, both during rush hour and in the late afternoon when there was less environmental electromagnetic noise. The recording time for each position was 1 minute. The whole procedure from recording to localization and imaging of the catheter tip in the phantom lasted about 5 minutes for each complete map. To test reproducibility, measurements were repeated five times during each session after manually repositioning the phantom under the Dewar vessel.

Results

The nine-channel MMCG system performed typically with a sensitivity of about $20 \text{ fT/Hz}^{0.5}$ in the frequency range of 1–100 Hz. After adaptive digital filtering of 50-Hz noise followed by time averaging, the signal quality was adequate for magnetic field reconstruction and source localization.

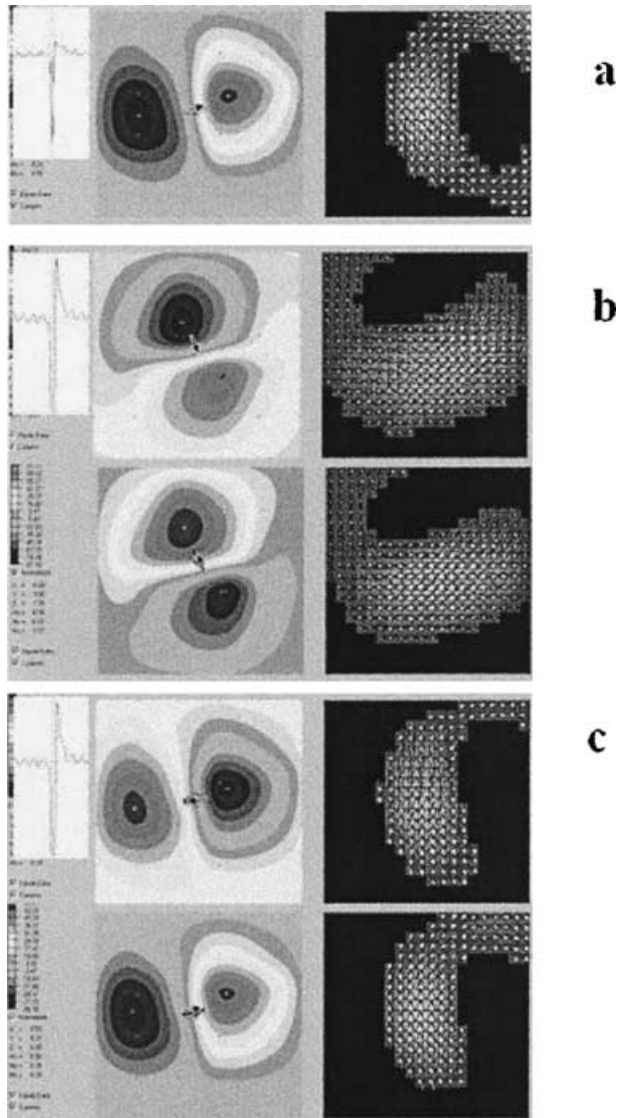


Figure 2. Examples of magnetic field distribution and inverse three-dimensional localization of the artificial current dipoles placed at the tip of the MultiMAP non-magnetic catheter in three different experiments (A, B, and C). DCI (black squares) provided an accurate image of current flow centered over the catheter tip. In each experiment, the catheter was intentionally moved a few millimeters in the X-Y plane. In (A) the source was a current dipole (a 10-mA monophasic signal of 2-ms duration). In (B) and (C) the source was a current dipole (a 10-mA biphasic signal of 10-ms duration).

Overall, 50 localizations were calculated from MMCG data for the two different positions of the catheter tip. The inverse localization of a dipolar source was accurate and reproducible, with both point-like source models (EMD or ECD), and with more advanced cardiomagnetic source imag-

ing based on the DCI model (Figs. 2 and 3). The last method provided immediate imaging of the direction of current flow, which was inverted with the change in polarity of the magnetic field distribution (Fig. 2).

Discussion

In clinical practice, MMCG is increasingly used for noninvasive functional cardiac imaging of electrophysiological phenomena and for the localization of the site of origin of cardiac arrhythmias.¹⁻¹¹ Earlier studies have demonstrated the reproducibility of MMCG cardiac source localization, with point-like (ECD) and DCI models, when MCGs were recorded in a MSR.¹³⁻¹⁷ This study was performed to evaluate the source localization accuracy of a novel MMCG system that was recently installed in the authors' unshielded hospital laboratory. It was used in the presence of other instrumentation for invasive electrophysiology, like multichannel electrogram recorders, monitors, and fluoroscopes,¹² which until now were considered incompatible with MMCG measurements. To use the MMCG in this environment, several fundamental problems affecting system reliability had to be identified and solved. As expected, the two major sources of environmental interference were radiofrequency and low frequency electromagnetic noise. The former can be strong enough to prevent effective functioning of the SQUID sensors. The latter, mainly power line interference and a result of low frequency vibrations, reduces the SNR and affects the sensitivity in the frequency range of interest for clinical MCGs (1-100 Hz). Both problems were overcome with improved technology, so that the nine-channel system is now operating with a sensitivity of about 20 fT/Hz^{0.5}, even during rush hour.

A minimum distance of 3-4 m between the MMCG system and other instrumentation was necessary to avoid interference with the magnetic sensors.

In comparison with the results obtained with the same investigational protocol in the Helsinki MSR,¹³⁻¹⁷ the unshielded MMCG provided equivalent reproducibility, but lower absolute accuracy (average three-dimensional error 9 vs 4 mm). However, it was confirmed that with an adequate SNR three-dimensional localization of the tip of the nonmagnetic catheter placed in the phantom at a distance from the sensors compatible with the midpoint of the ventricles is possible with unshielded MMCG. Most of the localization error was due to uncertainty in computing the depth of the source. This could be due in part to the straightforward use of the currently available software for calculating the inverse solution, designed for phantoms with geometry different from the simple

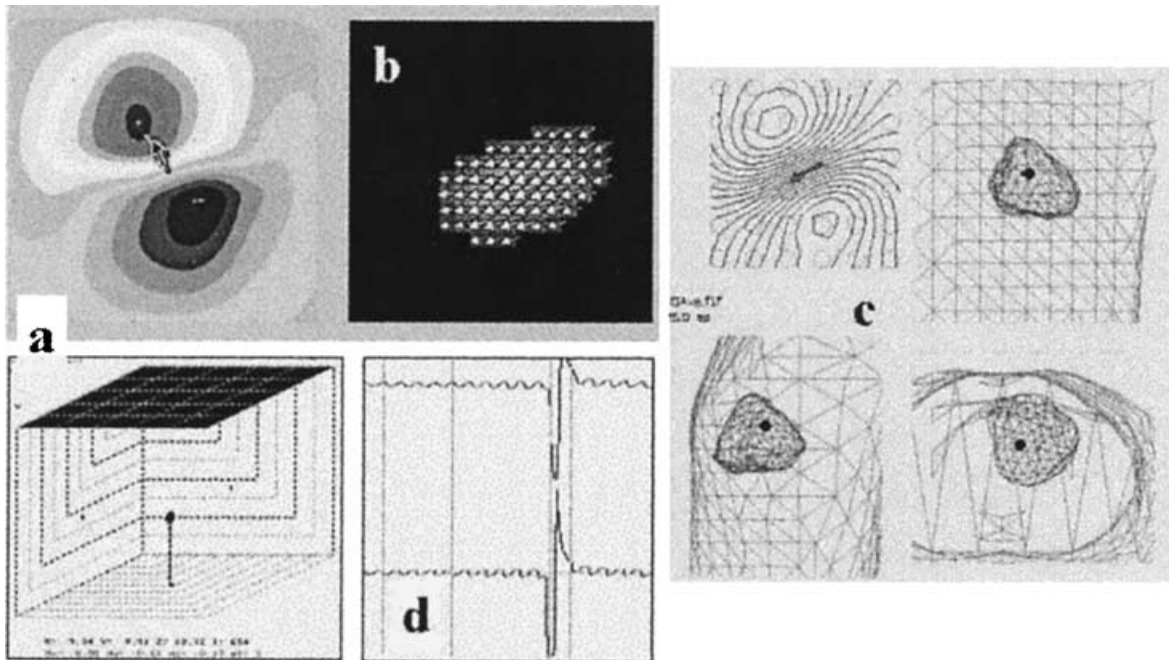


Figure 3. Example of three-dimensional localization of the artificial current dipoles at the tip of the MultiMAP non-magnetic catheter with (A) the effective magnetic dipole (EMD) model in a semiinfinite space, (B) the distributed currents imaging (DCI) model, and (C) the equivalent current dipole (ECD) model in a realistic torso, where the black dots mark the reproducibility of inverse localization in the three dimensions (averaged over five mapping sessions). In Panel D the waveform of the artificial dipole signal is also shown.

one used in this study. Moreover, some inaccuracy might also be due to the sequential mapping with the nine-channel system. It is anticipated that the latter problem will be overcome by upgrading the present system to 36 simultaneously recording channels. It is impressive that even with the limitations inherent in the nine-channel system, the localization accuracy was still good (three-dimensional localization error <10 mm) and the reproducibility was optimal. This confirms the intrinsic precision of the MMCG method. Finally, it was demonstrated that DCI is an accurate means of providing immediate information regarding the direction of current flow, which may be useful in interpreting clinical MMCG data correctly, for instance, in the localization of accessory pathways.

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Conclusion

In conclusion, this study demonstrates that although its absolute precision is lower than that achievable with MSRs, MMCG is highly reproducible even in unshielded clinical laboratories, and is accurate enough to be used clinically for noninvasive localization of cardiac arrhythmogenic substrates.²⁻¹¹

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