Europace Advance Access published July 12, 2006

Europace
doi:10.1093/europace/eul070

Comparison of magnetocardiography and electrocardiography: a study of automatic measurement of dispersion of ventricular repolarization

Fiona E. Smith[1]*, Philip Langley[1], Peter van Leeuwen[2], Birgit Hailer[3], Lutz Trahms[4], Uwe Steinhoff[4], John P. Bourke[5], and Alan Murray[1]

[1] *Medical Physics Department, Freeman Hospital Unit, University of Newcastle upon Tyne, High Heaton, Newcastle upon Tyne NE7 7DN, UK;* [2] *Research and Development Centre for Microtherapy (EFMT), Bochum, Germany;* [3] *Department of Medicine, Philippusstift, Essen, Germany;* [4] *Physikalisch Technische Bundesanstalt (PTB), Berlin, Germany; and* [5] *Academic Cardiology Department, Freeman Hospital, Newcastle upon Tyne, UK*

Received 10 November 2005; accepted after revision18 April 2006

KEYWORDS
Magnetocardiography;
Electrocardiography;
Dispersion of ventricular repolarization;
Electrocardiology;
Automatic measurements

Aims There is some dispute over the clinical significance of dispersion of ventricular repolarization measurements from the electrocardiogram. Recent studies have indicated that multichannel magnetocardiograms (MCGs), which non-invasively measure cardiac magnetic field strength from many sites above the body surface, may provide independent information from ECGs about ventricular repolarization dispersion. For this study, magnetocardiography and electrocardiography were compared from automatic measurements of dispersion of ventricular repolarization.

Methods and results Dispersion of ventricular repolarization time was determined in MCGs and standard ECGs recorded simultaneously from 27 healthy volunteers and 22 cardiac patients. Two automatic techniques were used to determine the interval of ventricular repolarization. There were significant differences in ventricular dispersion between ECG and MCG measurements, with multichannel MCG greater than ECG by 52 (47) ms [mean (SD)] ($P < 0.00001$) and 12-channel MCG greater by 17 (40) ms ($P < 0.004$) across techniques and all subjects. Magnetocardiograms had the greater discriminating power between normal and cardiac patients with differences of 46 (18) ms ($P < 0.017$) for multichannel MCG and 44 (16) ms ($P < 0.005$) for 12-channel MCG, compared with 16 (7) ms ($P < 0.04$) for ECG.

Conclusion Magnetocardiography has the power to discriminate regional cardiac conduction differences.

Introduction

Magnetocardiography is a non-invasive measure of the variation in magnetic field strength above the thorax and can be used to detect electromagnetic phenomena in the heart. The magnetic field sensors used to record magnetocardiograms (MCGs) are superconducting quantum interference devices (SQUIDs) that require liquid helium cooling.[1,2] The detectors are extremely sensitive and can measure the weak magnetic fields generated by the electrical activity of the heart. Because of their expense and the need for magnetic shielding, the diagnostic usefulness of MCG systems needs to be carefully assessed.

Many studies have demonstrated the potential benefit of magnetocardiography over electrocardiography for some clinical applications.[3–6] Magnetocardiograms have been found to be more accurate than ECGs for the diagnosis of right atrial hypertrophy and right ventricular hypertrophy and have been used to determine the location of conduction pathways in the heart non-invasively, making MCGs potentially beneficial for the localization of arrhythmia sources for catheter ablation.[4–6] Magnetocardiography has been shown to be useful for the identification of spatial current dispersion patterns, characterizing and separating Brugada syndrome and complete right bundle branch block.[7] Magnetocardiography can also detect circular vortex currents which give no ECG signal. As a result, MCG may show ischaemia-induced deviations from the normal direction of depolarization and repolarization better than or in a different way from ECGs.[8] The technique also offers a simple non-invasive method for

* Corresponding author. Tel: +44 191 233 6161 ext. 26667; fax: +44 191 213 0290.
E-mail address: f.e.smith@ncl.ac.uk

examination of the foetal electrophysiological signal, which is difficult to obtain from the surface ECG, and may be useful in antenatal assessment, identifying and classifying clinically relevant arrhythmias.[9–13]

From a clinical perspective, MCG has the major advantage over ECG of allowing the collection of electrophysiological waveforms without any physical contact between the device and the patient, and so problems arising from skin-electrode contact encountered in the ECG are avoided. Modern multichannel MCG measurement devices have typically more than 50 SQUID detectors and are able to detect the precordial magnetic fields originating from many sites over the heart with good signal-to-noise ratio and spatio-temporal signal resolution. The SQUID sensors are fixed inside the system, so that their relative positions are exactly reproducible in each patient measurement. Patient preparation is reduced to the removal of jewellery or magnetic items from clothes, so that typical multichannel MCG measurements take only 5–10 min in total.[14]

In addition, MCGs have the potential to give extra information over and above ECGs as they are able to detect the magnetic field that is produced by intracellular and extracellular currents in heart tissue. In comparison, only the effects of currents flowing through body tissue are detected by ECG.[15–17] Although the clinical significance of electrical QT dispersion from the electrocardiogram is uncertain, multichannel MCGs may allow a more sensitive calculation of the cellular dispersion of ventricular repolarization, because of the intrinsic differences between electric and magnetic cardiac fields, permitting regional as well as global differences in repolarization to be identified.[18] Dispersion information from electrocardiography is limited because current flow from any single localized region produces an ECG effect at almost any body surface location. In addition, discontinuities of the electric conductivity in body tissues like fat layers or bones act as spatial low-pass filters, and the information available on ventricular recovery times is influenced primarily by the maximum repolarization time and less by local inhomogeneities.[19] This is not the case for the magnetic signals.[20,21]

Many of the published studies suggesting the potential value of MCG contain no comparative ECG data.[22–24] Those that have comparative data generally use manual measurement,[25,26] which has been shown to be primarily influenced by T-wave amplitudes for both MCG and ECG.[27] Nevertheless, in some studies, MCGs have shown small, but significant, differences over ECGs, sometimes only when sophisticated indices have been used.[26,28] Automated measurements with ECGs have been shown to confer a significant advantage over manual measurement because automation can model the final stage of repolarization rather than attempt to determine the actual end of repolarization interval.[29] Automatic MCG and ECG dispersion measurements during cardiovascular autonomic function tests showed no correlation in one study, but because these measurements were in only 10 normal subjects, there is a need for a detailed and direct quantitative comparison of automatic measurements of dispersion of ventricular repolarization in MCGs and simultaneously recorded ECGs.[30] The aim of the study described here was to investigate and compare automatic measurements of dispersion from multichannel MCGs and 12-lead ECGs. Comparisons between MCG and ECG dispersion measurements were also made after making the number of ECG leads and MCG channels the same (12-channel MCG vs. 12-lead ECG).

Methods

Data collection

Simultaneous ECGs and MCGs were recorded from 27 healthy volunteers and a diverse range of 22 cardiac patients which could not be subdivided. There were 10 patients with evidence of myocardial infarction (MI), one of whom had left bundle branch block, and 12 patients with evidence of coronary artery disease, including two with possible MI and one with cardiomyopathy. Magnetocardiograms were obtained using a multichannel SQUID magnetometer system (Magnes 1300C, 4D Neuroimaging, San Diego, USA) installed inside a magnetically shielded room (AKb3, Vakuumschmelze, Hanau, Germany) in Bochum, Germany. The magnetometer consisted of 61 sensing channels for components of magnetic field normal to the frontal plane of the body surface (B_z) arranged as four concentric rings around a central sensor in a plane covering an overall approximate circular area of diameter 31 cm and area of coverage of 800 cm^2.[31,32] A diagram of the spatial arrangement of the 61 magnetic (B_z) channels is given in *Figure 1*. Twelve evenly spread MCGs were taken from the upper left area, as this region had previously shown the greatest range of automatic repolarization interval measurements in a separate group of subjects.[33] To avoid bias for one 12-channel set, four positions of 12-channel MCG were determined by systematically rotating the channels (from the initial position identified by a cross in *Figure 1*) by one channel in a clockwise direction.

An arrangement of 11 reference coils was used to detect ambient noise. Intrinsic system noise was less than 10 $fT/\sqrt{Hz}$ for frequencies >5 Hz. The multichannel device was placed as close to the thorax as possible, directly over the heart. In addition, 12-lead ECGs were recorded simultaneously with MCGs using non-ferrous sintered silver/silver chloride electrodes and

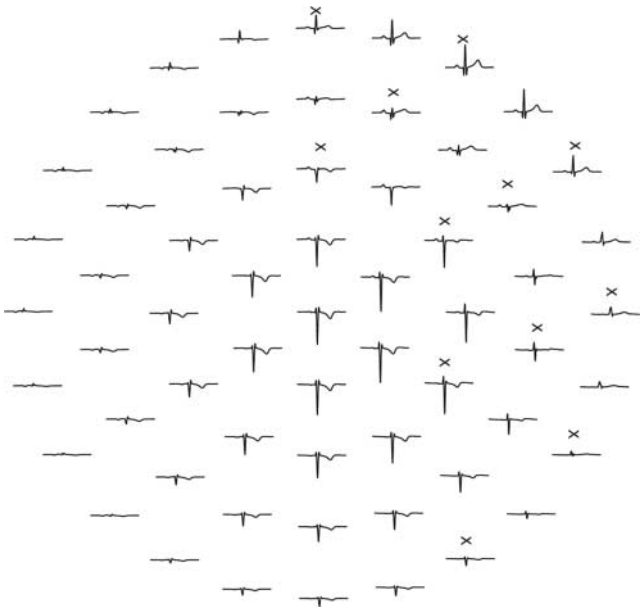

Figure 1 Schematic layout of the 61 MCG channels, as viewed on the subject. The head is at the top of the figure. The right side of the figure corresponds to the left side of the subject. The initial position of the 12 evenly spread MCG channels used for the 12-channel vs. 12-lead analysis are identified by a cross.

non-magnetic connecting wires. Magnetocardiogram and ECG data were recorded for 5 min at a sampling rate of 1 kHz and with a bandpass of 0.1–200 Hz.

Ventricular repolarization measurement

Computer software was developed in Matlab (Mathworks Inc., Matrix House, Cowley Park, Cambridge) to determine ventricular repolarization interval measurement. T-wave end was modelled using two automatic techniques.

PQRST features

Algorithms were developed to identify the following features in the MCG and ECG waveforms: P, R, and T-wave peaks, QRS onset, and baseline and T-wave amplitude. Peaks were identified using approximate initial locations detected manually and simultaneously for all channels/leads using interactive software. The actual peak values were found automatically by searching for local maxima or minima depending on the polarity of the channel/lead under analysis. For biphasic T-waves, both peaks were identified and the maxima or minima of the second peak was used if it was greater than the pre-determined noise threshold value. Baselines were selected interactively from a stable section of the T to P interval. Automatic measurements of T-wave amplitude were obtained from the peak of the T-wave to the TP baseline.

T-wave end detection

Automatic detection of T-wave end was by two techniques that used different methods based on terminal T-wave shape to model the end of the T-wave.[34] These algorithms do not attempt to replicate the manual end of QT measurements: previous studies have shown that the automatic algorithms are better able to discriminate between subject groups than manual measurement.[30] The slope technique used a linear model, and T-wave end was determined from the intersection of the line of best fit of the T-wave section lying between 70 and 30% of the peak of the T-wave with the TP baseline. The polynomial technique used a curve fitting method and T-wave end was determined from the peak of a second-order polynomial that was fitted to the 0.1 s interval of the T-wave following the point at which the amplitude fell to half-maximum. *Figure 2* illustrates the T-wave end detection techniques. Automatic repolarization interval, defined as the time between median QRS start in each subject and T-wave end, was determined in all channels/leads for all subjects.

Exclusion criteria

Small amplitude T-waves are known to increase ventricular repolarization measurement error in MCGs and ECGs; therefore, MCG channels with T-wave amplitudes less than 1 pT (1×10^{-12} T) and ECG leads with amplitudes less than 100 μV were automatically excluded from QT measurement.[35–37] All automatically measured MCGs were validated by manual inspection and, where erroneous measurements were made, these waveforms were excluded from the study. Subjects with fewer than five remaining ECG leads, after exclusions, were removed from the analysis.

Ventricular repolarization dispersion

Magnetocardiogram and ECG dispersion was determined automatically by calculating the range of repolarization intervals for each subject and for both techniques after applying exclusion criteria. The mean dispersion over the four orientations of 12-channel MCG was used for the 12-channel MCG data. A two-tailed Mann–Whitney *U* test was used to determine the significance of differences between automatic MCG and ECG dispersion and between the normal and cardiac groups. A significance level of $\leq$5% was considered statistically significant.

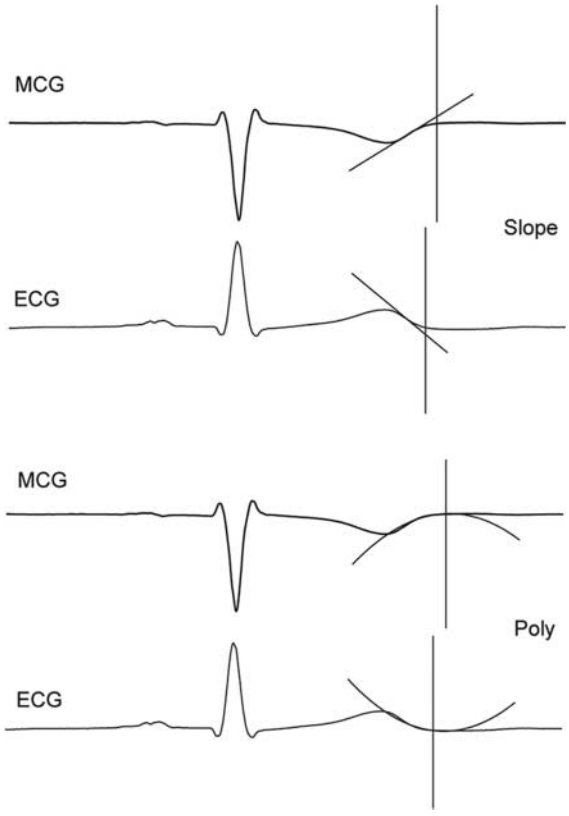

Figure 2 Illustration of the automatic techniques used to determine T-wave end in MCGs and simultaneously recorded ECGs. Intersection of the line of best fit between 70 and 30% of peak T-wave amplitude with the TP baseline (Slope) and the peak of the second-order polynomial best fit over the 0.1 s time interval starting at 50% peak amplitude (Poly).

Results

Exclusions

Three subjects were removed from the cardiac group, as their ECG leads fell to less than five after lead exclusions. The mean (SD) number of measured MCG channels was 49 (6) for the normal group and 46 (7) for the cardiac patients, out of a maximum of 61 recorded. For 12-channel MCG, an average of 9 (1) channels remained for the normal group and 9 (1) for the cardiac group. The mean number of remaining leads for ECG was 10 (1) for the normal group and 9 (2) for the cardiac group.

T-wave amplitude

The range of MCG and ECG T-wave amplitudes was similar for both normal subjects and cardiac patients, with the range of maximum T-wave amplitudes (and ratio of minimum to maximum) of 6–28 pT (0.2) for MCG and 143–917 μV (0.15) for ECG, over the study population.

Repolarization interval measurement

Figure 3 compares MCG and ECG repolarization interval measurements for the slope and polynomial techniques and the combined results from the average of both techniques. The mean repolarization interval measurement was 404 (40) ms for MCG and 389 (43) ms for ECG for the slope technique, with a Pearson correlation coefficient of

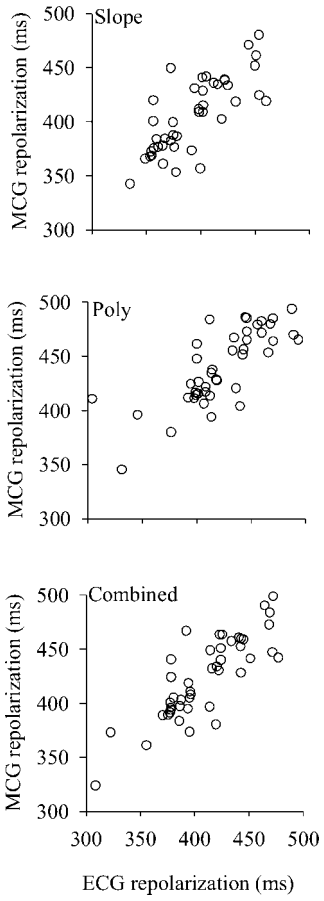

Figure 3 Repolarization interval measurements for MCG and ECG for all subjects.

0.8. For the polynomial technique, the mean repolarization interval for MCGs and ECGs was similar, with repolarization interval measurements of 447 (40) ms for MCG and 430 (44) ms for ECG and a Pearson correlation coefficient of 0.8. Measurements between techniques were highly correlated for both MCGs and ECGs, with Pearson coefficients of 1 for both comparisons. As there was no scientific reason for choosing one technique over the other, the automatic techniques were combined by averaging both techniques. The mean repolarization interval for the combined techniques was 425 (40) ms for MCG and 410 (44) ms for ECG, with a Pearson correlation coefficient of 0.8. The combined repolarization interval was used for all subsequent analyses.

Multichannel MCG and ECG dispersion of ventricular repolarization comparison

Figure 4 compares dispersion measurements for multichannel MCGs (MCG dispersion) and ECGs (ECG dispersion), illustrating that MCG dispersion was different and greater than ECG dispersion across all subjects. The paired difference between MCG and ECG dispersion is summarized in *Figure 5A*. Magnetocardiogram dispersion was greater than ECG dispersion in 44/46 (96%) subjects, with mean differences between MCGs and ECGs of 52 (47) ms ($P < 0.00001$) across all subjects.

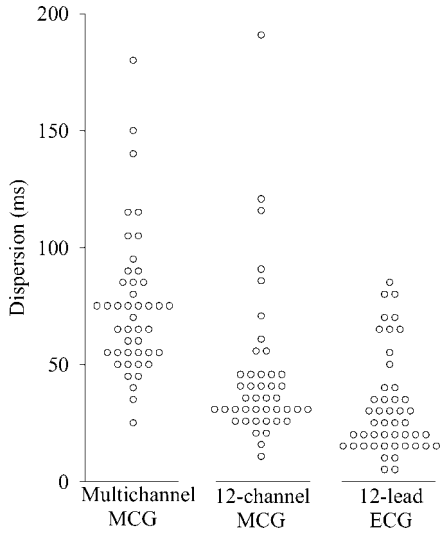

Figure 4 Dispersion of ventricular repolarization measurements for MCG (MCG dispersion) and ECG (ECG dispersion) for all subjects. Two values are off-scale.

12-Channel MCG and ECG dispersion of ventricular repolarization comparison

Figure 4 also compares dispersion measurements for 12-channel MCGs and 12-lead ECGs and shows that MCG dispersion was different and greater than ECG dispersion across all subjects even when the number of MCG channels was reduced. Paired differences in dispersion measurement for 12-channel MCGs and ECGs are summarized in *Figure 5B*. Magnetocardiogram dispersion was greater than ECG dispersion in 35/46 (76%) subjects, with mean differences between MCGs and ECGs of 17 (40) ms ($P < 0.004$) across all subjects.

Comparison between MCG and ECG dispersion measurements between normal and cardiac patients

Magnetocardiograms had the greatest discriminating power between the normal and cardiac groups with differences of 46 (18) ms ($P < 0.017$) for multichannel MCG and 44 (16) ms ($P < 0.005$) for 12-channel MCG. For ECG, differences of 16 (7) ms ($P < 0.04$) were obtained.

Relationship between MCG and ECG dispersion

Figure 6A shows the comparison between MCG and ECG dispersion for all subjects. The line of identity confirms that MCG dispersion was significantly greater than ECG dispersion ($P < 0.00001$). This result is explained by *Figure 6B* and *C*, which shows the maximum repolarization interval for MCG vs. that for ECG and minimum MCG repolarization interval vs. that for ECG repolarization, respectively. From the figure, the maximum repolarization interval in MCGs is significantly greater than in ECGs ($P < 0.0001$) and correlates highly with MCG dispersion, with a Pearson coefficient of 0.8. In contrast, there are no significant differences between minimum MCG and ECG repolarization interval measurements. These results show that differences in maximum repolarization interval between MCGs and ECGs significantly

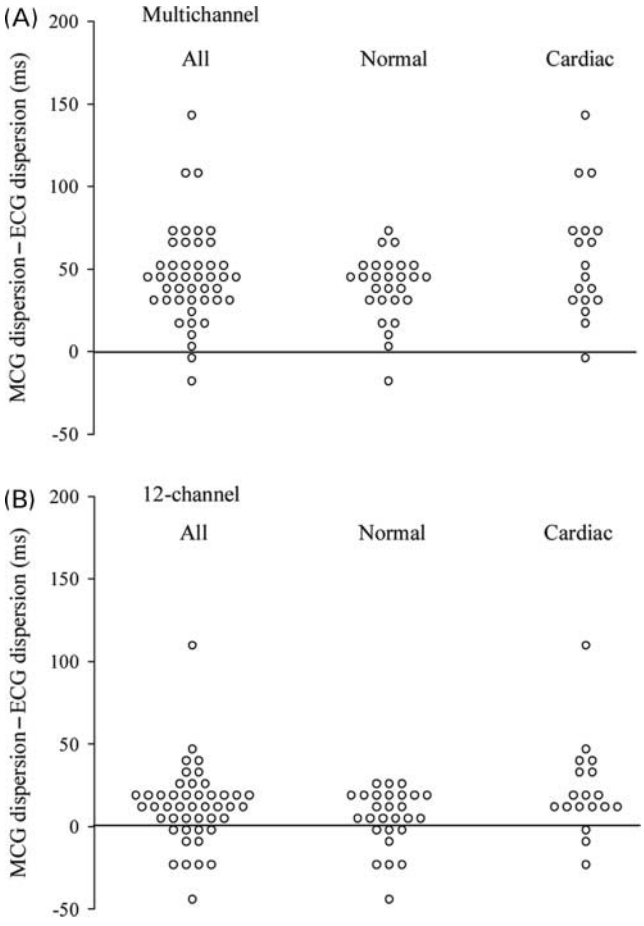

Figure 5 (*A*) Differences between MCG and ECG dispersion for all subjects and both subject groups. One value is off-scale. (*B*) Differences between 12-channel MCG and ECG dispersion for all subjects and both subject groups.

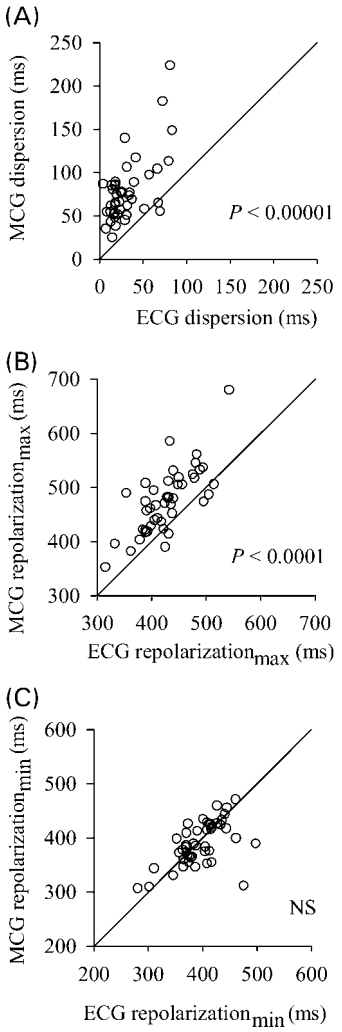

Figure 6 (*A*) Magnetocardiogram dispersion vs. ECG dispersion for all subjects. (*B*) Maximum MCG repolarization interval vs. maximum ECG repolarization interval for all subjects. (*C*) Minimum MCG repolarization interval vs. minimum ECG repolarization interval for all subjects.

contribute to the observed differences in MCG and ECG dispersion measurements.

Discussion

This study compared the automatic dispersion measurements from MCGs and ECGs and also assessed the effectiveness of MCGs and ECGs in differentiating between normal and cardiac patients. The most important results showed significantly different and greater dispersion measurements in MCGs compared with ECGs, with multichannel MCG greater in 96% (44/46) of subjects and 12-channel MCG greater in 76% (35/46) of subjects. Both MCG and ECG were able to discriminate between normal and cardiac groups. However, MCGs had the greatest discriminating power, with differences of 46 (18) ms and 44 (16) ms for multichannel and 12-channel MCG, respectively. The significantly greater dispersion from MCGs compared with ECGs indicates that MCG may contain regional information about the dispersion of ventricular repolarization. One possible explanation is that MCGs are more sensitive to tangential and vortex currents than ECGs and contain electrophysiological activity not contained in the ECG; this may contribute to the greater repolarization intervals in MCGs, particularly in patients with electrophysiological inhomogeneities due to anatomical disorders such as myocardial scar.[15,21]

The difference in repolarization dispersion of MCGs compared with ECGs is accepted in spite of some limitations that must be considered. The need for simultaneous 12-lead ECG and MCG measurements limited the number of recordings available for this study. In addition, 3/22 cardiac patients were unable to be measured using the automatic techniques, a limitation of our current algorithms which we intend to improve in future studies. We nevertheless have shown significant and consistent differences in the results of every comparison made. Differences between the number of recorded MCG channels and ECG leads should also be noted. Multichannel MCG measurements included more registration sites, which are not covered by the 12-lead ECG and which contain relevant information. We accept that to verify fully that MCGs contain more information will require comparisons with body surface ECG mapping.[8,29] However, to minimize the effect of these differences, we also compared 12-channel MCG and 12-lead ECG dispersion measurements. Although the standard 12-lead

ECG contains only 8 independent sources, all 12 leads are used clinically for patient diagnosis and no lead is independent, but all 12 give a different vector component, which is used in our analysis. The results from this analysis confirmed that dispersion in MCGs is significantly greater than ECG dispersion for all subjects even after significantly reducing the number of MCG channels. In addition, 12-channel MCG was better able than 12-lead ECG at separating the normal and cardiac patients. It can be noted that the mean differences between groups were very similar for multichannel MCG and 12-channel MCG. Finally, although there is some evidence that T-wave amplitudes influence manual QT measurement, with a doubling of T-wave amplitude increasing repolarization interval duration by $\sim$8 ms, no evidence exists for this effect in automatic measurements of repolarization interval.[34–36] In any case, the range of T-wave amplitudes in this study was similar for normal subjects and cardiac patients for both MCGs and ECGs.

Conclusion

In conclusion, there were differences in automatic ventricular dispersion measurements between multichannel MCGs and ECGs, with MCG dispersion significantly greater than ECG. These differences were also apparent after normalizing the number of MCG channels and ECG leads. Although both MCG and ECG dispersion measurements were able to distinguish between normal subjects and cardiac patients, significantly greater differences were obtained with MCG.

These results suggest that automatic dispersion measurements from multichannel MCGs contain different information from conventional ECG leads and indicate that magnetocardiography has the potential to provide further insights into the electromagnetic activity of the heart than standard electrocardiography, particularly for abnormalities involving ventricular repolarization.

Acknowledgements

The Engineering and Physical Sciences Research Council (GR/M97183/01) supported this research.

References

1. Hart G. Biomagnetometry: imaging the heart's magnetic field. *Br Heart J* 1991;**65**:61–2.
2. Cohen D, Edelsack EA, Zimmerman JE. Magnetocardiograms taken inside a shielded room with a superconducting point-contact magnetometer. *Appl Phys Lett* 1970;**16**:278–80.
3. Fenici R, Brisinda D, Meloni AM. Clinical applications of magneticardiography. *Expert Rev Mol Diagn* 2005;**5**:291–313.
4. Mori H, Nakaya Y. Present status of clinical magnetocardiography. *CV World Rep* 1988;**1**:78–86.
5. Nomura M, Nakaya Y, Saito K, Kishi F, Watatsuki T, Miyoshi H *et al*. Noninvasive localisation of accessory pathways by magnetocardiographic imaging. *Clin Cardiol* 1994;**17**:239–44.
6. Nomura M, Nakaya Y, Fujino K, Ishihara S, Katayama M, Takeuchi A *et al*. Magnetocardiographic studies of ventricular repolarization in old inferior myocardial infarction. *Eur Heart J* 1989;**10**:8–15.
7. Kandori A, Shimizu W, Yokokawa M, Noda T, Kamakura S, Miyatake K *et al*. Identifying patterns of spatial current dispersion that characterise and separate the Brugada syndrome and complete right-bundle branch block. *Med Biol Eng Comput* 2004;**42**:236–44.
8. Hänninen H, Takala P, Mäkijärvi M, Montonen J, Korhonen P, Oikarinen L *et al*. Recording locations in multichannel magnetocardiography and body surface potential mapping sensitive for regional exercise-induced myocardial ischemia. *Basic Res Cardiol* 2001;**96**:405–14.
9. Van Leeuwen P, Hailer B, Bader W Geissler J, Trowitzsch E, Grönemeyer DH. Magnetocardiography in the diagnosis of foetal arrhythmia. *Br J Obstet Gynaecol* 1999;**106**:1200–8.
10. Kandori A, Hosono T, Kanagawa T, Miyashita S, Chiba Y, Murakami M *et al*. Detection of atrial-flutter and atrial-fibrillation waveforms by fetal magnetocardiogram. *Med Biol Eng Comput* 2002;**40**:213–7.
11. Quartero HWP, Stinstra JG, Golbach EGM, Meijboom EJ, Peters MJ. Clinical implications of fetal magnetocardiography. *Ultrasound Obstet Gynecol* 2002;**20**:142–53.
12. Wakai RT, Strasburger JF, Li Z, Deal BJ, Gotteiner NL. Magnetocardiographic rhythm patterns at initiation and termination of fetal supraventricular tachycardia. *Circulation* 2003;**107**:307–12.
13. Van Leeuwen P, Lange S, Klein A, Geue D, Gronemeyer DH. Dependency of magnetocardiographically determined fetal cardiac time intervals on gestational age, gender and postnatal biometrics in healthy pregnancies. *BMC Pregnancy Childbirth* 2004;**4**:6.
14. Steinhoff U, Knappe-Grueneberg S, Schnabel A, Smith F, Langley P, Murray A, Koch H. Magnetocardiography for pharmacology safety studies requiring high patient throughput and reliability. *J Electrocardiol* 2004;**37**:187–92.
15. Kandori A, Hosono T, Chiba Y, Shinto M, Miyashita S, Murakami M *et al*. Classifying cases of fetal Wolff–Parkinson–White syndrome by estimating the accessory pathway from fetal magnetocardiograms. *Med Biol Eng Comput* 2003;**41**:33–9.
16. Koch H, Haberkorn W. Magnetic field mapping of cardiac electrophysiological function. *Philos Trans R Soc Lond* 2001;**359**:1287–98.
17. Wikswo JP, Barach JP. Possible sources of new information in the magnetocardiogram. *J Theor Biol* 1982;**95**:721–9.
18. Antzelevitch C, Shimizu W, Yan GY, Sicouri S. Cellular basis for QT dispersion. *J Electrocardiol* 1997;**30**:168–75.
19. Brockmeier K, Schmitz L, Bobadilla Chavez J, Burghoff M, Kovh H, Zimmermann R *et al*. Magnetocardiography and 32-lead potential mapping: the repolarization in normal subjects during pharmacologically induced stress. *J Cardiovasc Electrophysiol* 1997;**8**:615–26.
20. Bradshaw LA, Wijesinghe RS, Wikswo JP Jr. Spatial filter approach for comparison of the forward and inverse problems of electroencephalography and magnetoencephalography. *Ann Biomed Eng* 2001;**29**:214–26.
21. Bradshaw LA, Richards WO, Wikswo JP Jr. Volume conductor effects on the spatial resolution of magnetic fields and electric potentials from gastrointestinal electrical activity. *Med Biol Eng Comput* 2001;**39**:35–43.
22. Dutz S, Bellemann ME, Leder U, Haueisen J. Investigation of passive myocardial vortex currents in an anthropomorphic phantom. *Biomed Tech* 2003;**48**:230–1.
23. Van Leeuwen P, Hailer B, Wehr M. Spatial distribution of QT intervals: an alternative approach to QT dispersion. *Pacing Clin Electrophysiol* 1996;**19**:1894–9.
24. Hailer B, van Leeuwen P, Lange S, Groenemeyer D, Wehr M. Spatial dispersion of the magnetocardiographically determined QT interval and its components in the identification of patients at risk from arrhythmia after myocardial infarction. *Ann Noninvasive Electrocardiol* 1998;**3**:311–8.
25. Korhonen P, Vaananen H, Makijarvi M, Katila T, Toivonen L. Repolarization abnormalities detected by magnetocardiography in patients with dilated cardiomyopathy and ventricular arrhythmias. *J Cardiovasc Electrophysiol* 2001;**12**:772–7.
26. Hailer B, Van Leeuwen P, Lange S, Pilath M, Wehr M. Coronary artery disease may alter the spatial dispersion of the QT interval at rest. *Ann Noninvasive Electrocardiol* 1999;**4**:267–73.
27. Oikarinen L, Viitasalo M, Korhonen P, Vaananen H, Hänninen H, Montonen J *et al*. Postmyocardial infarction patients susceptible to ventricular tachycardia show increased T wave dispersion independent of delayed ventricular conduction. *J Cardiovasc Electrophysiol* 2001;**12**:1115–20.
28. Oikarinen L, Paavola M, Montonen J, Viitasalo M, Mäkijärvi M, Toivonen L, Katila T. Magnetocardiographic QT interval dispersion in postmyocardial infarction patients with sustained ventricular tachycardia: validation of automated QT measurements. *Pacing Clin Electrophysiol* 1998;**21**:1934–42.
29. Van Leeuwen P, Hailer B, Lange S, Groenemeyer D. Spatial distribution of repolarization times in patients with coronary artery disease. *Pacing Clin Electrophysiol* 2003;**26**:1706–14.
30. Langley P, Murray A. Comparison of manual and automatic QT dispersion measurements in clinical groups. *Comput Cardiol* 2001;**28**:645–8.
31. Van Leeuwen P, Geue D, Lange S, Cysarz D, Bettermann B, Groenemeyer D. Is there evidence of fetal-maternal heart rate synchronization? *BMC Physiol* 2003;**3**:2.

32. Van Leeuwen P, Haupt C, Hoormann J, Hailer B, Mackert BM, Stroink G. A 67 channel biomagnetometer designed for cardiology and other applications. In: Yoshimoto T, Kotani M, Kuriki S, Karibe H, Nakasato N, eds. *Recent Advances in Biomagnetism*. Sendai: Tohoku University Press; 1999. 89–92.
33. Smith FE, Langley P, Trahms L, Steinhoff U, Bourke JP, Murray A. Comparison of cardiac magnetic field distributions during depolarization and repolarization. *Int J Bifurcation Chaos* 2003;**13**:3783–9.
34. Smith FE, Langley P, Trahms L, Steinhoff U, Bourke JP, Murray A. Comparison of automatic repolarization measurement techniques in the normal magnetocardiogram. *Pacing Clin Electrophysiol* 2003;**26**: 2096–102.
35. Murray A, McLaughlin NB, Bourke JP, Doig JC, Furniss SS, Campbell RW. Errors in manual measurement of QT intervals. *Br Heart J* 1994; **71**: 386-90.
36. Smith FE, Langley P, Trahms L, Steinhoff U, Bourke JP, Murray A. Errors in cardiac repolarization measurement using magnetocardiography. *Pacing Clin Electrophysiol* 2002;**25**:1223–9.
37. Langley P, Di Bernardo D, Murray A. Effect of lead exclusion for the manual measurement of QT dispersion. *Pacing Clin Electrophysiol* 2001;**24**:75–8.