Noninvasive, direct visualization of macro-reentrant circuits by using magnetocardiograms: initiation and persistence of atrial flutter

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Aims We analysed the cardiac magnetic fields on the body surface to visualize electrical currents noninvasively during reentrant arrhythmias.

Methods and results Seven patients with counterclockwise atrial flutter (AFL) were studied during 17 episodes of AFL using 64-channel magnetocardiograms (MCGs) and electrophysiological study. Eight of the episodes were paroxysmal AFL, in which MCGs were recorded from the time of spontaneous onset to the time of termination. We constructed iso-magnetic field maps of the tangential components and produced MCG animations. With respect to AFL initiation, an atrial premature complex induced AFL. Prior to the initiation of AFL, atrial fibrillation (AF) transiently occurred. The cardiac magnetic fields revealed a single peak during sinus rhythm or with premature complexes but a disorganized pattern during AF. When AF transformed to AFL, the magnetic fields changed from a disorganized pattern to a single peak at first and then evolved to a circular pattern. During persistent AFL, the magnetic source moved in a counterclockwise circuit.

Conclusion MCG animation can be used to visualize the sequence in which a premature complex transforms sinus rhythm to AFL via AF. Our findings indicate that MCGs can be used to identify noninvasively the mechanisms responsible for atrial tachyarrhythmias.

Key Words: Atrial flutter, atrial fibrillation, cardiac mapping, magnetocardiograms, magnetic source, tangential components.
right atrium\textsuperscript{[17–19]. In AFL, the reentrant circuit is almost circular in the anterior–posterior view\textsuperscript{[19], and the cardiac magnetic fields in the anterior chest should be detectable.

**Methods**

**Patients**

We analysed 17 episodes of counterclockwise AFL in seven patients (six men and one woman) using 64-channel MCGs (Hitachi, Japan). Five patients had cardiovascular disease (two with hypertension, one with mitral stenosis, one with ischaemic heart disease, and one with hypertrophic cardiomyopathy) and two had normal cardiac structures (Table 1). Patients with permanent pacemakers or prosthetic valve placement were excluded from this study because of the presence of excessive magnetic noise in MCGs. Antiarrhythmic drugs had been discontinued for more than five half-lives before the procedures.

All seven patients were diagnosed as having counterclockwise AFL based on the findings on ECGs and electrophysiological study (EPS, bandpass filter: 30–400 Hz). Atrial activation was indicated by a negative ‘saw tooth’ pattern in the inferior ECG leads and counterclockwise activation along the tricuspid annulus during EPS\textsuperscript{[20]. Nine of the 17 episodes were persistent AFL of at least 3 weeks duration. Eight of the 17 episodes were paroxysmal AFL in the same individual, patient 1. Patient 1 had short and frequent episodes of paroxysmal AFL induced by atrial premature complexes. For the eight episodes, the average duration time, from the onset of the atrial premature complex that induced AFL to the termination of AFL, was 11.2 ± 7.9 s (range: 4.2–21.9 s).

This study was approved by the ethics committee of the Tsukuba University Hospital, Tsukuba, Japan. All patients gave written informed consent before entering the study.

**MCGs**

A 64-channel MCG system was placed in a magnetically shielded room at the University of Tsukuba, Tsukuba, Japan. In this system, a detection coil was used as a first order gradiometer. The measurement area was 17.5 by 17.5 cm (sensor interval: 2.5 cm, sensor arrangement: 8 by 8 matrix, Fig. 1). The distance between the chest wall and the SQUID sensor was about 4.5 cm. Signal to noise ratio and magnetic detection limit were approximately 4 and 7 femto tesla/√Hz. In this study, we analysed beat-to-beat components without signal averaging and baseline correction. Without baseline correction or signal averaging, some SQUID sensors detected magnetic noise <5 pico tesla (pT)/m even if there was no electrophysiological phenomenon, for example, between the end of a T-wave end and the beginning of a P-wave during normal sinus rhythm. Therefore, differentiating electrophysiological phenomena from noise for signals <5 pT/m was difficult.

The cardiac magnetic fields were recorded from the anterior chest for 2 min. An ECG lead II (bandpass filter: 0.1–100 Hz) was simultaneously recorded. We measured the normal components of the cardiac magnetic fields (sampling interval: 1 ms (1 kHz); bandpass filter: 0.1–50 Hz) and calculated the tangential components of the cardiac magnetic fields using the equation\textsuperscript{[21,22],}

\[
B_{xy} = \sqrt{\left(\frac{\partial B_z}{\partial x}\right)^2 + \left(\frac{\partial B_z}{\partial y}\right)^2}
\]

where \(B_z\): the measured-normal components (pT) and \(B_{xy}\): the calculated-tangential components (pT/m). In the analysis of the normal components, the cardiac magnetic strength, just above a magnetic source (i.e. an electrical source), is zero. However, the magnetic strength is maximal in the tangential components\textsuperscript{[23,24].}

To visualize reentrant circuits, we then created isomagnetic field maps of the tangential components and produced an MCG animation loop (a minimal interval of 1 ms (1 kHz), a maximal recording time of 2 min). An atrial animation was made from the data in which atrial components were clearly identified during long R–R intervals in order to differentiate atrial components from ventricular components. Arrows were added to the maps to emphasize the relationship between the cardiac magnetic fields and the electrical currents\textsuperscript{[24]. The arrows indicate electric currents calculated from the cardiac magnetic fields.

**Table 1 Clinical characteristics of study patients**

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Cardiovascular disease</th>
<th>Cardiothoracic ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>55</td>
<td>Hypertension</td>
<td>48</td>
</tr>
<tr>
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<td>Hypertension</td>
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</tr>
<tr>
<td>3</td>
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<td>Mitral stenosis</td>
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<tr>
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<td>Male</td>
<td>51</td>
<td>None</td>
<td>52</td>
</tr>
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<td>Male</td>
<td>51</td>
<td>None</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>Male</td>
<td>74</td>
<td>Ischaemic heart disease</td>
<td>54</td>
</tr>
<tr>
<td>7</td>
<td>Male</td>
<td>69</td>
<td>Hypertrophic cardiomyopathy</td>
<td>57</td>
</tr>
</tbody>
</table>

Mean ± standard deviation 60 ± 9

51 ± 4
Comparison between MCGs, ECGs, and EPS

MCGs and EPS were performed on the same day in different rooms, MCGs in a magnetically shielded room and EPS in an electrophysiological laboratory. We compared MCGs animation loops, ECGs, and EPS at the three time points: initiation of AFL, ongoing AFL, and termination of AFL and characterized the relationship between atrial activation and the cardiac magnetic fields.

Results

Beat-to-beat atrial activation was analysed in all 17 episodes using 64-channel iso-magnetic field maps.

AFL initiation

Spontaneous AFL onsets were studied in patient 1 (Figs. 2 and 3). An atrial premature complex (Fig. 2A) induced atrial fibrillation (AF; Fig. 2B), which then transformed to AFL (Fig. 2C). Two 20-polar catheters were placed in the right atrium. One catheter (RA, 2–5 mm, Daig, Nihon Kohden, Japan) was placed in the posterior right atrium. The other catheter (Halo catheter, 2–5–2 mm, Daig, Nihon Kohden, Japan) was placed along the tricuspid annulus. The earliest recording was recorded at RA 3–4 during sinus rhythm (Fig. 2A, the first beat) and RA 5–6 during an atrial premature complex (Fig. 2A, the second beat). Left atrial mapping was not performed in this patient. During AFL, atrial activation revealed counterclockwise rotation along the tricuspid annulus (Fig. 2C).

Eight spontaneous onsets were recorded using MCGs in patient 1 (Fig. 3). For this episode, the time from the onset of the atrial premature contraction (Fig. 3A-2) to the termination of AFL was 21.9 s. The ECG from lead II shows 'saw tooth' flutter waves (Fig. 3A-7) for 12.9 s of the total duration time.

During sinus rhythm, atrial activation started from the upper left area of the map (red area in Fig. 3B-1). The atrial premature complex (Fig. 3B-2) also started near the region of earliest activation for sinus rhythm in this patient. There were differences in activation time and the shape of the cardiac magnetic fields between sinus rhythm (Fig. 3B-1) and the premature complex (Fig. 3B-2). However, both sinus rhythm and the atrial premature complex had cardiac magnetic fields with a single peak of 60 pTm⁻¹. The cardiac magnetic fields during AF (0.7 s after the premature complex, Fig. 3B-3) showed a disorganized pattern. Specifically, multifocal magnetic sources in the animation activated randomly (Fig. 3B-3, B-4). The cardiac magnetic strength decreased with each peak (40–45 pTm⁻¹). Two seconds later, the cardiac magnetic fields fused into a single peak (Fig. 3B-5), but were still irregularly activated. They then evolved into a circular pattern of activation (Fig. 3B-6). Fifteen seconds later (Fig. 3A-7), the cardiac magnetic fields were represented by a red
Achalomalgal flutter (AFL) persistence

During AFL, the cardiac magnetic fields showed a circular pattern with counterclockwise rotation (Fig. 4) in all seven patients. The cardiac magnetic strength during AFL was 46 ± 14 pTm⁻¹ (range: 25–71 pTm⁻¹).

AFL termination

In patient 1, the AFL sequence terminated when atrial activation passed from the right lateral wall of the right atrium to the coronary sinus ostium, as demonstrated by EPS. In MCGs, the atrial components were obscured by the ventricular components during all eight episodes of termination. Therefore, we could not analyse the termination phase using iso-magnetic field mapping.

Discussion

In this study, we analysed reentrant arrhythmias using MCGs. Our system utilizes a new technique, employing a multi-channel system, beat-to-beat analysis, and tangential-component MCGs. The cardiac magnetic fields revealed a single peak during sinus rhythm, a circular pattern during AFL, and a random pattern during AF. Our results demonstrate that unique MCG patterns are associated with AFL and AF.
We were able to visualize transient AF, which antedated AFL. Waldo et al. reported that a transitional rhythm, usually AF, is required for the initiation of type I AFL [25]. When AF transformed to AFL, the cardiac magnetic fields fused a single peak at first, and then changed to a circular pattern. EPS identified a wave front for reentrant arrhythmia using a bandpass filter of 30–400 Hz [26]. Regardless of whether invasive [27,28] or noninvasive procedures are used, it is difficult to measure the refractory period [29] and the excitable gap [30,31]. However, the iso-magnetic field map showed a circular pattern during the persistent phase of AFL. This suggests that MCGs can be used to detect myocardial activities at the wave front and to determine the refractory periods.

The circular patterns obtained by MCGs were larger than reentrant circuits obtained by EPS. The wavelength of the circular pattern was 7.8–12.3 cm during AFL [32].

Figure 4  Counterclockwise atrial flutter in patient 2. Atrial activation showed counterclockwise rotation along the tricuspid annulus with endocardial mappings (A). From top to bottom displayed as electrocardiogram lead I, II, V1, endocardial bipolar catheter from the high right atrium, His bundle, Halo catheter 19–20, 17–18, 15–16, 13–14, 11–12, 9–10, 7–8, 5–6, coronary sinus proximal, coronary sinus mid, and coronary sinus distal. (B) Shows iso-magnetic field maps at 15-ms intervals. The magnetic source (red area) showed a large circuit with counterclockwise rotation. ECG indicates electrocardiogram; HRA, high right atrium; His, His bundle; Halo, Halo catheter; CS Prox, coronary sinus proximal; CS Dist, coronary sinus distal; and pT, pico tesla.
However, the area of the circle identified by MCGs was as large as the measuring area of 17.5 cm². The circular patterns are theoretically affected by the number, size, location, and shape of reentry. The circuit enlarges as the distance between the magnetic source and the SQUID sensors increases. A simulation showed the upper link of AFL, anterior or posterior to the superior vena cava, affects the circular patterns, circular or semicircular. As left atrial mapping was not performed in this study, the diagnosis of patient 1 may be controversial. It is not clear if a macro-reentry in the right atrium was built due to focal AF originating from the left atrium. However, in this study we showed the relationship between the cardiac magnetic fields and atrial activation in the right atrium (AFL: a circular pattern, AF: disorganized pattern). Further studies are required to differentiate atrial activation in the right atrium and those in the left atrium and to classify AFL patterns, such as lower loop reentry and a circuit in the posteromedial right atrium (sinus venosus), based on MCGs.

The tangential-component MCG can also be applied to the evaluation of ventricular arrhythmias. The cardiac magnetic fields generated during ventricular tachycardia may be more complex than those generated during AFL because the reentry circuit is small and complex in old myocardial infarctions.

**Study limitations**

This study had some associated limitations. First, EPS and MCGs were performed in different rooms, and were not done at the same time. Although ECG lead II was simultaneously recorded as a standard, more information was required to analyse AF in patient 1. Second, standard MCG maps have not been established. There might be differences between electric currents measured by EPS and the arrows generated by the iso-magnetic field maps. In the MCG animation representing a 1- or 2-ms interval, we can identify electric currents through simple movements of the magnetic source, which were summarized as arrows on the maps. The magnetic source moved along a circuit in AFL, but rapidly disappeared during AF. These changes were not completely reproduced in the sequential maps. We must identify a better way to reproduce this information. In addition, imaging three-dimensional information is also important.

**Conclusion**

We analysed the tangential components of cardiac magnetic fields in patients with counterclockwise AFL. MCG animation revealed the sequence of activation in which a premature complex transformed sinus rhythm into AFL via AF. This suggests that MCGs can be used to diagnose atrial tachyarrhythmias noninvasively and to investigate mechanisms of how AF converts to AFL.

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**References**


