Transmembrane Potential Properties at the Core of Functional Reentrant Wave Fronts in Isolated Canine Right Atria

Charles A. Athill, MD; Takanori Ikeda, MD; Young-Hoon Kim, MD; Tsu-Juey Wu, MD; Michael C. Fishbein, MD; Hrayr S. Karagueuzian, PhD; Peng-Sheng Chen, MD

Background—The characteristics of transmembrane potential (TMP) at the core of functional reentry in the atrium are not well understood.

Methods and Results—In protocol 1 (11 dogs), isolated perfused canine right atria were mapped from the endocardial surface while simultaneous TMPs were recorded from the epicardial surface. Episodes of reentry (n = 64) were induced in the presence of 1 to 5 μmol/L acetylcholine. Successful simultaneous TMP recordings and activation maps were made in 8 episodes. The TMP was “near the core” if it was within 3.2 mm of the core; otherwise, it was considered to be “in the periphery.” The mean cycle length of reentry was 110 ± 35 ms. The TMP amplitude, duration (90% repolarization), and (dV/dt)max near the core (n = 106) were 58 ± 22 mV, 46 ± 14 ms, and 33 ± 20 V/s, respectively, significantly less than those in the periphery (n = 241): 70 ± 8 mV, 94 ± 32 ms, and 55 ± 10 V/s (P < 0.001 for all). In 2 episodes of reentry, the cell at the core remained unexcited at its resting membrane potential. In protocol 2 (2 dogs), we performed simultaneous high-density mapping in 4 episodes of reentry and showed synchronous activation patterns on both surfaces with similar locations of the core.

Conclusions—During meandering functional reentry in isolated canine right atria, (1) TMPs of cells near the core have a reduced amplitude, duration, and (dV/dt)max, and (2) cells at the core may remain unexcited at their resting membrane potential. These findings are compatible with the spiral wave concept of functional reentry in the atrium. (Circulation. 1998;98:1556-1567.)

Key Words: waves • atrium • arrhythmia • tachycardia • electrophysiology

Functional reentry, a well-documented mechanism of cardiac arrhythmia, refers to propagation of an impulse around a core determined by the electrophysiological properties of the tissue. Allessie et al measured transmembrane potential (TMP) of stationary reentrant wave fronts in isolated rabbit atria. On the basis of the results of that study, they proposed the “leading circle” concept to explain the mechanisms of functional reentry in the atria. The maintenance of leading circle reentry (the absence of short-circuiting) was due to repetitive centripetal wavelets that kept the core in a constant state of refractoriness. The leading circle hypothesis also proposed that the head of a reentrant wave front bites its own tail, resulting in little or no excitable gap. In comparison, other investigators proposed that in addition to refractoriness, the wave front curvature is also important in the maintenance of functional reentry. The curvature of a reentrant wave front progressively increases as one approaches the central core. When a critical curvature is reached, propagation fails despite the presence of excitable tissue. The point at which propagation fails is the site of a wave break. The area encircled by the wave breaks is the core of reentry. According to this hypothesis, the core of functional reentrant wave front may remain excitable but unexcited. Compatible with the latter hypothesis, experimental data obtained from thin slices of ventricular tissues revealed that there was a progressive reduction of the amplitude of the action potential (AP) as the recording site moved from the periphery toward the core of reentry. At the core itself, the electrical activity had a very low amplitude. However, because optical mapping techniques used in the latter studies sample from a group of cells rather than a single cell and cannot give the value of resting potential of the cells, the excitability of the cells at the core of functional reentry remains unclear. We recently developed a model of functional reentry in isolated superfused canine atrial tissues in which the location of the core could be determined accurately with computerized mapping techniques. By analyzing extracellular bipolar electrogram recordings, we found that the core of stationary functional
reentry in this model remained excitable but unexcited. However, no TMP was recorded in that study, and therefore the TMP properties near the presumed excitable core could not determined. To study the TMP properties of the core, we induced functional reentry in the isolated perfused canine right atrium using a model previously reported by Schuessler et al. The patterns of activation on the endocardial surface were registered with computerized mapping techniques while TMP was recorded simultaneously from an epicardial site with a standard glass microelectrode. With these methods, we could determine the relative location of the TMP electrode on the epicardium and the core of functional reentry on the endocardium. The purpose of the present study was to characterize the TMP profile of cells at the core of functional reentry in the canine right atrium to test the hypotheses that the core of functional reentry in atrial tissues is excitable but remains unexcited and that a large excitable gap is present near the core of functional reentry.

**Methods**

**Tissue Preparation**

The research protocol was approved by the institutional animal care and use committee of the Cedars-Sinai Medical Center and followed the guidelines of the American Heart Association. Thirteen mongrel dogs weighing between 9 and 23 kg (mean ± SD, 19 ± 5 kg) were anesthetized with sodium pentobarbital (30 to 35 mg/kg), intubated, and ventilated with room air by a respirator (Harvard Apparatus). The chest was opened through a median sternotomy, and the heart was rapidly removed. The right coronary artery was immediately cannulated and perfused at 10 mL/min with oxygenated and warmed (36.5°C) Tyrode’s solution. The right atrial appendage and the free wall were then excised, along with the proximal portion of the right coronary artery. The distal portion of the right coronary artery was ligated, and branches to the residual right ventricular tissue were cauterized to enhance perfusion to the right atrium. The tissue was then placed in a tissue bath with dimensions of 10.2×7.2×2.7 cm, superfused with oxygenated Tyrode’s solution, and mounted on the mapping plaque with the endocardial surface down (Figure 1A). The details of this recording electrode array and the composition of the Tyrode’s solution were reported elsewhere. The temperature in the bath was maintained at 36.5°C and the pH at 7.4.
Protocol 1: TMP Characteristics During Reentry

Recording Electrodes
In protocol 1, we mapped the endocardium in 11 isolated canine right atria with a high-resolution electrode plaque while simultaneously recording TMP from the epicardial surface roving microelectrode. Figure 1B shows the recording plaque array.4,5 The recording plaque measured 3.2×3.8 cm and consisted of 509 electrodes. Because of technical difficulties, the first 32 electrodes were not used for recording; leaving a total of 477 recording bipolar electrodes available for the study. The interelectrode distance was 1.6 mm, and the interpolar distance was 0.5 mm, measured from center to center. The recording electrodes were connected to a computerized mapping system (EMAP, Uniservices). The electrograms were filtered with a high-pass filter of 0.5 Hz and were acquired at 1000 samples per second with 16 bits of accuracy.6,8

In each study, a bipolar electrode (interpol distance, 0.5 mm) was placed on the epicardial surface. This electrode was used to calculate activation differences between the epicardium and the endocardium. With the S₁ or S₂ stimulus used as a reference point, the activation times of the epicardial bipole and the corresponding endocardial bipole on the mapping plaque were recorded, and the difference was determined during pacing and during reentry.

TMP Recordings
TMPs were recorded from the epicardial surface (Figure 1A) with conventional machine-pulled, glass capillary electrodes filled with 3 mol/L of KCl with a tip resistance of ~20 MΩ. The electrodes were coupled by silver–silver chloride wire in a right-angle micropipette holder leading to a high-input impedance and variable-capacitance neutralization amplifier (IE-251, Warner Instrument Corp).9 The data were acquired by AIXON TL-140 A/D acquisition hardware and Axoclamp-2A software (Axon Instruments, Inc) and were digitized at 1 kHz with 12 bits of accuracy. The sites of the TMP recordings were marked with insect pins that penetrated both the tissue and the recording plaque electrode array. At the end of the study, the tissue was lifted slightly to allow determination of the location of the pin on the recording electrode plaque (channel number). The tissue with the pin in place was then removed from the plaque and tissue bath.

Stimulation Protocol
A bipolar stimulating electrode (S₁) was placed at the middle lower edge of the epicardial surface to deliver baseline pacing with 5-ms pulse widths at twice diastolic threshold current. After 8 beats at a cycle length of 300 ms, a premature stimulus was given at twice diastolic threshold current to determine the refractory period at the S₁ site. Another pair of stimulation electrodes was placed 0.5 to 1.0 cm away from the S₁ electrode, near the center of the mapping plaque, to give premature stimulation (S₂) to induce reentry.7 After 8 S₁ stimuli at a cycle length of 300 ms, an S₂ was introduced to scan the vulnerable period. The initial strength of S₂ was 5 mA. If repetitive activations were not induced, the strength of S₂ was increased at 1-mA steps until the induction of reentry or when 25 mA was reached. If the arrhythmia was not induced at baseline, 1 to 5 μmol/L acetylcholine was added to the perfusate, and the same induction protocol was repeated. Once reentry was induced, simultaneous endocardial activation mapping and epicardial TMP recordings were performed. The mapping system allowed data to be acquired continuously for 8 seconds.

Protocol 2: Simultaneous Endocardial and Epicardial Mapping
In protocol 2, simultaneous endocardial and epicardial maps from 2 additional isolated canine atria were obtained during reentry. Two mapping electrode plaques were used (Figure 1C). One contained 416 electrodes and was used to map the endocardium in the manner described above. A second recording plaque (2.1×2.1 cm) consisting of 96 electrodes was placed on the epicardial surface to register simultaneous activations. TMP was not recorded in this protocol.

Data Analyses
A reentrant wave front was defined as a wave front that completed a circular pathway and reentered the area of origin.3 The approximate location of the core was identified by dynamic display as the area encircled by the reentrant wave front.4,6 TMP recordings near the “core” of reentry were defined as recordings within 2 bipolar electrodes (3.2 mm) of the core. The recordings made at distances >3.2 mm from the core were considered in the “periphery” of the reentry. The time of activation was taken as the time of the largest dV/dt, and the patterns of activation were displayed dynamically.9,10,12

At the conclusion of each study, the atrial tissue, with the insect pin at the TMP recording site, was fixed in 10% neutral buffered formalin. Cross sections were taken from epicardium to endocardium at the TMP recording site. The cross sections were stained with hematoxylin-eosin to determine tissue thickness, myocardial fiber orientation, and the presence, if any, of tissue abnormalities.

All statistical analyses were done with GBSTAT.13 The results were expressed as the mean±SD. Paired Student’s t tests were used to compare mean cycle lengths, AP amplitudes, AP duration at 90% repolarization (APD₉₀), and (dV/dt)ₘₐₓ. The null hypothesis was rejected at a value of P<0.05.

Results
Protocol 1
Progressively faster pacing from the S₁ site was routinely performed at baseline to detect areas of conduction slowing and conduction block. Figure 2 shows an isochronal map of activations during baseline S₁ pacing from the middle lower edge of the isolated right atrial myocardium. Propagation proceeded without evidence of conduction block. Because of the heterogeneity in atrial tissue structure, the conduction velocity varied in both orthogonal directions. This phenomenon is manifested on the isochronal map by the variations of the distances between isochronal lines. Figure 2B shows bipolar recordings from selected (circled) channels during S₁ pacing. No evidence of conduction block was observed in this tissue or in the remaining 10 tissues studied.

Electrophysiological parameters were measured at baseline and after perfusion with acetylcholine. The mean effective refractory period was 168±18 ms (n=11), with an S₁-S₁ interval of 300 ms. With the addition of 1 to 5 μmol/L acetylcholine, the mean effective refractory period decreased to 100±17 ms (n=11) compared with baseline (P<0.001). There was significant shortening of APD₉₀ during acetylcholine infusion, 76±8 ms (n=11) compared with 180±16 ms (n=11) at baseline (P<0.01). The mean AP amplitude and (dV/dt)ₘₐₓ at baseline were 78±17 mV and 71±6 V/s (n=11), compared with 82±10 mV and 68±4 V/s (n=11), respectively, after the addition of acetylcholine (P=NS for both comparisons). The mean epicardial-endocardial delay was 4±3 ms (n=11) during S₁ pacing at 300 ms. During reentry, the epicardial-endocardial delay increased to 15±6 ms (n=24). The epicardial-endocardial delay during reentry was significantly greater than the delay during S₁ pacing (P<0.001).

Reentry was not inducible without acetylcholine. A total of 64 episodes of functional reentry (5.8±6 episodes per tissue; range, 0 to 17) were induced in the presence of acetylcholine. Successful simultaneous TMP recordings and activation maps were obtained in 8 of these 64 episodes of reentry. These 8 episodes were from 4 tissues. The 3 episodes in
which the core of TMP was registered were from 2 different
tissues.

**TMP Properties Near the Core of Reentry**
In 3 of the 8 episodes, the TMP recordings were within
3.2 mm of the core of reentry. These 3 episodes were from
dogs 1 and 3. A total of 106 reentrant activations from these
3 episodes were analyzed (Table). Figure 3 displays a
computerized dynamic activation display of 3 cycles of
reentry during a sustained episode induced in dog 3. The
activation wave front proceeds in a clockwise direction
around the core denoted by the circle. Two complete rotations
are displayed (panels A through H). The site of the TMP
recording is indicated by an asterisk and is within 2.6 mm of
the core of reentry.

Figure 4A displays slightly later activations of the same
episode of reentry as that shown in Figure 3. Functional
reentry continues in a clockwise direction. The core meanders
slightly (1.6 mm) in the southeast direction from 4A through
4E. In 4E, the core visits the TMP recording site. The core
then meanders in the northwest direction, then southeast once
again to visit the recording site (4J) a second time. Figure 4B
shows an endocardial bipolar electrogram recording at the
core of functional reentry, showing characteristic double
potentials.

The TMP recordings corresponding to the activations
shown in Figures 4 and 5 are displayed in Figure 5 and
labeled 1 to 13. In the squares at the bottom of the figure, we
show the location of the core (ellipse), the site of TMP
recordings (asterisk), and the site of epicardial bipolar record-
ing (plus sign). This figure illustrates that TMP recordings
near the core of reentry show marked variations in amplitude
and duration. The amplitude and duration of the TMP depend

Transmembrane Potential at the Core of Reentry

<table>
<thead>
<tr>
<th></th>
<th>Near Core (n=106)</th>
<th>Periphery (n=241)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP amplitude, mV</td>
<td>58±22</td>
<td>70±8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>APD90, ms</td>
<td>46±14</td>
<td>94±32</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>(dV/dt)max, V/s</td>
<td>33±20</td>
<td>55±10</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cycle length, ms</td>
<td>143±29</td>
<td>95±30</td>
<td>&lt;0.001</td>
</tr>
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</table>

AP indicates action potential; APD90, action potential duration measured from
the onset of action potential to 90% repolarization.
on the relative proximity of the TMP recording to the core. When the 2 were close to each other (2 and 3), there was a significant reduction of TMP amplitude and duration. When the 2 overlapped (7 and 9), the TMP stayed at roughly 2.65 mV, indicating that it was excitable but remained unexcited. The simultaneously recorded epicardial bipolar electrogram (Figure 5, top) opposite channel 384 in the periphery of reentry showed minimal variations of activation cycle length.

The TMP from another episode of reentrant activity is shown in Figure 6A, from dog 3. This episode was registered immediately after the induction of reentry by the S1-S2 protocol. The TMPs labeled 1, 2, and 3 correspond to the S1, S2, and the first reentrant activation, respectively. During the second cycle of the induced reentry, no TMP was recorded (labeled 4). Simultaneous computerized mapping data (not shown) revealed that the core of reentry was visiting the TMP site. Figure 6B shows that TMP during pacing immediately after the episode in Figure 6A terminated. The AP amplitude was >70 mV, indicating that the altered TMP characteristics were unrelated to recording instabilities. In a total of 5 instances, including the 3 shown in Figures 3 to 6, the impaled cell remained near resting membrane potential during reentry when the core approached the vicinity of the TMP recording site. In these 5 instances during 2 episodes of reentry, the TMP averaged 3.0 ± 1.5 mV above the maximum diastolic potential. These findings indicate that at least 1 cell at the core of functional reentry remained excitable but unexcited during reentry.

When TMP recordings were made near the core, the AP amplitude, APD90, and (dV/dt)max were significantly reduced compared with those in the periphery (Table). The presence of large diastolic intervals of the APs near the core implies that an excitable gap is present during functional reentry, consistent with our previous findings.6,11
Figure 4. Computerized dynamic display pattern corresponding to activations 6, 7, 8, 9, and 10 in Figure 5. A, Counterclockwise reentrant excitation as indicated by arrows. Ellipse indicates location of core. *Epicardial TMP recording location; +bipolar electrogram recording location. Numbers below each panel indicate times of activation, with beginning of data acquisition as time zero. B, Endocardial bipolar electrograms from contiguous electrodes at core of reentry. Bipolar electrograms show double potentials (arrowheads). Long arrows indicate direction of reentrant excitation. Site of TMP recording is directly opposite electrode 266, which has double potentials of equal size.
TMP Properties at the Periphery of Reentry

The TMP recordings at the periphery were registered in 5 episodes of sustained reentry from dogs 1, 8, and 10, for a total of 241 reentrant activations (Table). Figure 7A shows the dynamic activation display of an episode of functional reentry in dog 10. The reentrant wave front propagates in a clockwise direction in the far right upper quadrant. A single complete rotation around a stationary core (indicated by the ellipse) with a cycle length of 118 ms is displayed. The activation spreads peripherally from the core to activate the rest of the tissue. The activation wave front reaches the epicardial bipolar recording site (indicated by a plus sign) at 58 ms and the TMP site (indicated by an asterisk) at 66 ms during this rotation. The TMP site is in the periphery, 27.5 mm away from the core. The TMP recordings (Figure 7B) show a stable cycle length of reentry of 118 ms without cycle length variation. The AP amplitude, APD90, and (dV/dt) max for this episode remained constant and were 63 ± 1 mV, 100 ± 1 ms, and 58 ± 6 V/s. There were no variations in the cycle length or action potential characteristics in this episode and in the remaining 4 episodes of functional reentry.

Figure 7C displays selected endocardial bipolar electrograms located in the periphery of reentry. As the tip of the wave front propagates clockwise around the core, it sequentially activates sites a through f. A single rotation of the reentrant wave front is displayed. The arrows indicate the direction of wave propagation.

Protocol 2: Simultaneous Endocardial and Epicardial Mapping

To ensure that the core of reentry was in a similar location on both the endocardial and epicardial surfaces, we performed simultaneous mapping on both sides of 2 isolated atrial tissues. A total of 4 episodes were recorded. All showed that the reentrant wave front on the endocardium and epicardium propagated in the same direction, with the core at the same location. Figure 8A shows an example. A single counterclockwise reentrant wave front was present during sustained reentry with a cycle length of 115 ms. The upper sections of each panel display maps from the endocardial surface, and the lower sections display maps from the epicardial surface. The lower right panel shows the direction of wave propagation (arrows) and the locations of the core on both endocardial and epicardial surfaces. The core was at the same location on both surfaces of the atrium. Figure 8B shows the actual bipolar electrogram recorded during the same episode of reentry.

Discussion

TMPs at the Core of Functional Reentry

Using simultaneous computerized mapping and standard glass microelectrode recordings, we recorded TMPs near the core and at the periphery of functional reentry in isolated canine atria. A major finding of the present study is the demonstration of quiescent cells at the core during function-
ally based reentrant excitation, consistent with an excitable but unexcited state. In addition, APs of cells near the core of reentrant activity have a reduced amplitude, duration, and \((dV/dt)_{\text{max}}\) compared with cells at the periphery. Although we were not able to register TMPs simultaneously from the core and from the periphery, only the TMP near the core showed large variations of amplitude, duration, and \((dV/dt)_{\text{max}}\). Furthermore, excitable but unexcited cells were registered only at the core. These findings support the conclusion that there is reduced amplitude, duration, and \((dV/dt)_{\text{max}}\) near the core and that the cells at the core were excitable but remain unexcited.

In the Belousov-Zhabotinskii chemical reaction, which generates self-perpetuating spiral waves,\(^{14}\) light intensity modulations at the core are less than in the surrounding area, indicating an area of reduced activity.\(^{15}\) Pertsov et al\(^2\) demonstrated a gradual decrease in AP amplitude as recordings approached the core during reentry in thin sheets of sheep ventricular tissue. Because optical mapping techniques register from a group of cells, the resting membrane potential of a single cell was not defined in that study. In the present study, we found that the TMPs at the core in the 5 recorded instances during 2 episodes of reentry were only 3.0±1.5 mV above the maximum diastolic potential. In some episodes, the cell at the core remained at its maximum diastolic potential. These findings clearly indicated that the cells at the core remained unexcited.

A second implication of these findings is that the excitable gap is larger near the core than in the periphery of the reentry. The diastolic interval, or the difference between the cycle length of reentry (110 ms) and the APD\(_{90}\) (46 ms), was 64 ms near the core. In comparison, the diastolic interval was <20 ms in the periphery. We have demonstrated in another study.

**Figure 6.** TMP at core of reentry. This is a different episode from that shown in Figures 3 to 5. A, Epicardial bipolar electrograms corresponding to channel 384 and microelectrode TMP recordings at channel 266 during nonsustained episode of reentry. Activations are labeled 1 to 5. Activation 4 is recorded from center of core. B, Pacing immediately after episode recorded in A. Note that resting membrane potential is same as that in A and that normal action potential amplitudes are recorded. See text for details.
using isolated swine ventricular tissues that in a stable functional reentrant circuit, only a thin layer of activation, a few millimeters thick, was responsible for sustaining reentry. The activation in the periphery was due to outward propagation of the activation from this thin layer of reentrant excitation. If the results of the latter study are applicable to atrial tissues, then the excitable gap of reentrant activity in the atria should be determined by the diastolic interval near the core (≈50% of the cycle length) and not by the diastolic interval distant from the core (≈20% of the reentrant cycle length). The presence of a large excitable gap in functional reentry in the atria is incompatible with the leading-circle concept.

Variation of Morphological Characteristics of TMP Near the Core
A feature commonly observed in computer simulation and in experimental studies of functional reentry is the meandering nature of the spiral wave. The velocity of meandering determined whether the arrhythmia was compatible with tachycardia or fibrillation. In this study, we recorded TMP during episodes of atrial tachycardia, with a single reentrant wave front in the entire mapped region. The TMP registered distant from the core always demonstrated regular and consistent morphology. Conversely, the TMP near the core was irregular in cycle length, with variable morphology and amplitude. These findings are compatible with the spiral wave theory, which predicts that the path of a functional reentrant wave front often is not fixed but rather meanders slightly from activation to activation. However, the resolution of our mapping techniques did not allow us to determine whether or not the path of the reentrant waves had a distinct signature, as was demonstrated by computer simulations.

An additional factor that may contribute to meandering is the complex atrial structure. For example, the thickness of the atrium increases significantly at the site of pectinate muscle...
Figure 8. Simultaneous endocardial and epicardial activation during reentry. A, Activation patterns on endocardial (ENDO) and epicardial (EPI) surfaces during episode of reentry. Reentrant wave front rotates in counterclockwise direction as indicated by arrows. Numbers below each panel represent time in milliseconds, with beginning of data acquisition as time zero. Bottom right, Schematic of activation pattern of reentry on both surfaces. Circle indicates location of core. B, Selected electrograms registered by electrodes several millimeters from core during same episode of reentry.
bundles. This variable thickness may result in significant source-sink mismatch and Wenckebach-like pattern of conduction block, as shown in Figure 5. However, we have examined our tissue specimen. The core of functional reentry shown in Figure 5 was not located at the site of a pectinate muscle. Therefore, we do not think that the pectinate muscle structure is responsible for the activation patterns shown in Figure 5.

**Mechanism of Functional Reentry in Canine Atrial Tissues**

Spiral wave theory predicts that the core is excitable yet remains unexcited. Self-sustaining spiral waves are generated in myocardial tissues when 2 waves meet at a critical temporal and spatial location, inducing a wave break. The tip of the wave break has a pronounced curvature, which results in a very low margin of safety for propagation. Therefore, the tissue ahead is not excited, even though it is fully excitable. The wave front propagates around the unexcited area, the core, without invading or short-circuiting the core. In other words, the “source-sink mismatch” is the basis for cessation of propagation into the core, thereby preventing the short-circuiting and termination of reentry. A corollary to this hypothesis is that the core should remain excitable rather than refractory. It is therefore possible to excite the core of functional reentry by electrical stimulation or by a propagating wave front, resulting in termination or displacement of the core. The demonstration of fully excitable cells (TMP at or near resting membrane potential) at the core of functional reentry by the present study further strengthens the hypothesis that source-sink mismatch resulted in the failure of propagation toward the core. Because (dV/dt)_max is proportional to the safety factor of propagation, these findings also support the hypothesis that failure of propagation may occur more easily near the core than away from the core. The results of the present study are compatible with a previous study that shows a quiescent core with extracellular recordings, and they support the spiral wave concept of functional reentry in the atria.

**Limitations of the Study**

The lack of action potential duration and effective refractory period measurements at the cycle length comparable to the reentrant cycles (110±35 ms) is a limitation of this study. However, during attempts to pace the atria at 110-ms cycle lengths, arrhythmia was often induced, making the testing of effective refractory period difficult. An alternative method is to give premature stimulus during the reentrant excitation and test the effective refractory period. This was done in our previous studies in the same animal model. For a reentrant excitation with a cycle length of 120 ms, the excitable gap was ~38 ms. There was no postrepolarization refractoriness. Furthermore, regenerative action potentials were inducible during phase 3 repolarization. In Figure 7B of the present study, we also demonstrate that atrial cells were excitable almost as soon as they repolarized. These findings indicate that there was no postrepolarization refractoriness in the atria mapped. The quiescent phase 4 intervals shown in Figures 5 and 6 are not the result of postrepolarization refractoriness.

Although our results are not compatible with the leading circle concept of functional reentry, these results may be applicable only to the model used in this study. It is possible that in other animal models or in humans, the leading circle concept is still applicable to the reentry in atria. The number of episodes in which TMP recordings were successfully obtained was small. Therefore, the present study cannot provide a certain answer to whether the mechanism of reentry is, in general, spiral waves.

A third limitation is that, because of technical difficulties, the mapping was done on the endocardial surface, whereas the TMP was registered on the epicardial surface. Although we performed separate studies to show that the reentrant wave fronts mapped on both surfaces were of the same cycle length, had the same direction of rotation, and shared the same core, there is still a possibility that the TMP is not registered at or near the core of reentry in the reentrant episodes studied. This possibility and the small number of successful impalements at or near the core are important limitations of the study.

**Conclusions**

In this study, we registered TMP near the core and at the periphery of functional reentrant wave fronts in isolated, perfused canine atrial tissues. The TMP at the core showed large variations of amplitude and morphology, with long diastolic intervals, implying the presence of a significant excitable gap. The cells at the core were quiescent, with TMP near or at the maximum diastolic potential. These findings imply that the functional reentrant wave fronts in the atrial tissues are not leading circles. Rather, they exhibit the major characteristics observed in the spiral waves of excitation.

**Acknowledgments**

This work was done during the tenure of an NIH Postdoctoral Fellowship Grant to Dr Athill, a Cedars-Sinai Burns and Allen Research Institute Fellowship Grant to Dr Ikeda, a Research Fellowship from the Division of Cardiology, College of Medicine, Korea University to Dr Kim, an Electrocardiographic Heartbeat Organization Award to Dr Karagueuzian, and an AHA/Wyeth-Ayerst Established Investigatorship Award and the Pauline and Harold Price Endowment to Dr Chen and was supported in part by a Specialized Center of Research (SCOR) Grant in Sudden Death (P50-HL-52319) and research grants (HL-50259 and HL-44880) from the National Institutes of Health and the Ralph M. Parsons Foundation. The authors wish to thank James N. Weiss, MD, for his support; Peter Hunter, PhD, David Bullivant, PhD, Sylvain Martel, PhD, and Serge LaFontaine for constructing the mapping system; and Dr Chun Hwang for making the tissue chamber used in this study. We also thank Masaaki Yashima, MD, Avile McCullen, Meiling Yuan, and Dustan Hough for technical assistance and Elaine Lebowitz for secretarial assistance.

**References**

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_Circulation_. 1998;98:1556-1567
doi: 10.1161/01.CIR.98.15.1556

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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