Simultaneous Multisite Mapping of the Right and the Left Atrial Septum in the Canine Intact Beating Heart

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Background—The spread of activation between the right atrium (RA) and left atrium (LA), particularly along the right and left aspects of the interatrial septum, is not clear.

Methods and Results—Basket-shaped catheters carrying 64 electrodes were deployed into both the RA and LA of 10 dogs. Position and orientation of the baskets were determined by fluoroscopy and echocardiography. Basket unipolar electrograms were simultaneously recorded in each dog during sinus rhythm, right ventricular pacing, and pacing of the right septum through the basket in the superior and inferior regions. Isochrone maps depicting all aspects of the atria, including the septum, were compared. During sinus rhythm and superior right septal pacing, wave fronts propagated predominantly from superior to inferior regions on both the right and left septum. However, activation of the left septum was delayed compared with the right septum. During right ventricular pacing and inferior right septal pacing, activation of the septum was discordant; 1 wave front propagated rapidly on the right septum from inferior to superior regions, whereas 2 opposing wave fronts originated on the left septum in both the superior and inferior regions. The left septum was activated predominantly by the superior wave front. Activation of the left septum was completed in a significantly shorter time during pacing of the right septum in the inferior region compared with the superior region.

Conclusions—In dogs, activation of the right and left aspects of the interatrial septum is discordant. Electrical connections are present between the RA and LA in regions superior as well as inferior to the septum. (Circulation. 1999;100:312-319.)

Key Words: atrium • conduction • mapping

Radiofrequency catheter ablation has all but eliminated the need for surgery for most supraventricular arrhythmias, has further advanced our understanding of electrophysiological mechanisms of arrhythmias, and has brought to our attention properties of particular regions of the atria.1–3 The interatrial septum plays an important role in intra-atrial as well as interatrial conduction4–5 and is involved in the initiation and maintenance of tachyarrhythmias such as atrioventricular nodal reentry tachycardia,6,7 atrial flutter,8,9 and atrial fibrillation.10,11 Previous simultaneous mapping studies of the intact right atrium (RA) and the left atrium (LA) were limited to the epicardium,12,13 whereas simultaneous multisite endocardial mapping studies were performed only in the RA.14,15 Since the description of Bachmann’s bundle as the major conduit between the atria,16,17 little is known about other electrical connections between the RA and LA and their role in the spread of activation, particularly along the septum. Mapping the activation patterns simultaneously on the right and left aspects of the septum and on a beat-by-beat basis enables us to identify regions of electrical linkage between the atria and to better understand their role during normal and abnormal atrial rhythms, which may further improve therapy with catheter ablation or pacing.18

The objectives of the present study were (1) to determine the activation patterns along the interatrial septum during normal and paced rhythms by simultaneously mapping the right and left aspects of the septum in the canine intact beating heart and (2) to ascertain the contribution of the interatrial septum to electrical connections between the RA and LA.

Methods

Animal Preparation

Ten mongrel dogs of both sexes (weight, 20 to 30 kg) were included in the study. Once anesthesia was induced with pentobarbital 30 mg/kg, the dogs were endotracheally intubated and ventilated with an external respirator. The chest was opened via a median sternotomy, and the heart was suspended in a pericardial cradle. Right and left femoral veins were isolated. Continuous intravenous saline infusion was maintained through the left femoral vein. The study was conducted in accordance with institutional guidelines.
Catheter Introduction and Placement

Basket-shaped catheters carrying 64 electrodes (model Constella; Boston Scientific/EP Technologies) were used in the study. The basket consisted of 8 flexible splines, each carrying 8 electrodes that were equally spaced at 3 or 4 mm apart, with a deployed diameter of 38 or 48 mm, respectively. A basket catheter was inserted through an 11F guiding sheath in the right femoral vein and deployed in the RA. A second basket catheter was inserted through an 11F guiding sheath via a purse-string suture in the LA appendage.

Under the guidance of fluoroscopy, the sheath was initially inserted into the inferior right pulmonary vein with the tip extending beyond the cardiac silhouette. The sheath was gradually withdrawn to the pulmonary vein ostium, where the basket was expanded (Figure 1A).

Basket position and orientation in the RA and LA were guided by fluoroscopy and epicardial echocardiography. Distinct markers on 2 splines allowed identification of the expanded basket splines and their orientation under fluoroscopy. A 5-MHz transesophageal echocardiography transducer (model OmniPlane II and SONOS 2000; Hewlett Packard) was used on the epicardium to acquire images from different planes (Figure 1B and 1C). The following criteria were adopted while the basket catheters were being positioned. (1) The baskets were deployed and expanded so that the splines were not constantly in touch with one another. Spline contact with the endocardium was confirmed by capturing the atrium during pacing through spline electrodes. Echocardiography was used to verify expansion of the basket splines against the septum (Figure 1C). Three basket splines were consistently maintained in contact with the right and left septum in the anterior, middle, and posterior aspects. (2) The tip of the RA basket was at the junction of the appendage and the superior vena cava and was confirmed by visual and physical inspection. Splines facing the tricuspid annulus could not capture the atrium, and electrograms recorded from those splines were consistently low in amplitude. Inferior (proximal) electrodes of the septal splines were positioned at the level of the coronary sinus ostium. (3) Position and orientation of the baskets were further verified at the completion of the experiment by careful dissection of the atria and visual inspection of the splines with respect to anatomic features.

Electrophysiology Protocols

Intracardiac basket electrograms were initially recorded during sinus rhythm. Electrograms were then recorded while the right ventricle (RV) was paced through an epicardial electrode pair. Bipolar pacing was then applied through electrode pairs on the RA basket splines in the anterior, middle, and posterior aspects of the septum, in both the superior and inferior regions of the septum, as illustrated in Figure 2A.

All pacing protocols were performed at a cycle length of 350 ms in all 10 dogs and at an amplitude just above the pacing threshold with an external stimulator (model S8800; Astro-Med). The pacing protocols were also repeated at a cycle length of 300 ms in the initial 5 dogs. A switch box connected to the RA basket catheter allowed selection of electrode pairs on the basket for pacing while they were recorded from all electrodes simultaneously.

Unipolar electrograms from both the RA and LA baskets, along with a surface ECG (leads I, II, and III), were acquired simultaneously during all protocols with a 256-channel cardiac mapping system (model CardioMapp; Prucka Engineering) that amplified and displayed the signals at a 1-ms sampling interval per channel. The common reference electrode was placed on the right leg.

Data Analysis and Display

Activation times were derived from simultaneous unipolar basket electrograms by computer-automated determination of the time of occurrence of the negative peak of the first derivative of each atrial electrogram. Visual verification was performed in the presence of double potentials, where the activation time was assigned to the major deflection. Simultaneous isochrone maps of the RA and LA were constructed to display activation sequences throughout the entire atrial surfaces, including the right and left aspects of the interatrial septum. The maps were plotted on 2-dimensional grids by unrolling the baskets with the endocardium viewed from inside the atrial cavity. Detailed analysis of activation was focused on the septal portion of the isochrone maps. Three consecutive beats were analyzed for each protocol, and the results were averaged over the 3 beats. All data were analyzed and verified by 2 experienced persons.

Continuous variables were compared by Student’s t test for paired data or ANOVA for repeated measures. To isolate sources of

Figure 1. A, Anteroposterior radiograph of 2 basket catheters deployed in RA and LA. B and C, Two-dimensional echocardiographs of a dog heart, obtained at different instants of heartbeat, showing expansion of 2 baskets and their separation by interatrial septum. Basket septal splines are marked by white arrowheads. LV indicates left ventricle.
differences, multiple comparisons were made with the Bonferroni t test. Data were expressed as mean±SD. A value of \( P < 0.05 \) was considered statistically significant.

Definitions

The boundaries of the right septum were defined as illustrated in Figure 2A. The superior right atrium was at the same level as the top of the tricuspid annulus. The anterior right septum was marked by a spline at the junction of the septum and tricuspid annulus, anterior to the coronary sinus ostium. The middle right septum was identified by a spline posterior to the anterior spline and situated at or behind the coronary sinus ostium. This spline was generally located anterior to or in the middle of the fossa ovalis. The posterior right septum was identified by a spline posterior to the middle septum, located behind the fossa ovalis.

The boundaries of the left septum were defined as illustrated in Figure 2B. The superoanterior left septum was identified by the insertion of Bachmann’s bundle. Insertion of Bachmann’s bundle was initially identified during sinus rhythm as the site of earliest activation in the LA and was further confirmed after dissection of the LA and visual inspection. The inferoposterior left septum was identified at the inferior right pulmonary vein, and the inferoanterior left septum was determined by the mitral valve.

The region of initiation of activation on the right or left aspect of the septum was identified by the septal spline electrode with the earliest activation time, whereas time for completion of activation on either aspect of the septum was identified by the septal spline electrode with the latest activation time. The onset of earliest activation in the RA basket was selected as the time reference during sinus rhythm, whereas the stimulus artifact was selected as the reference during pacing.

Results

Based on basket interelectrode spacing, the distance between the superior and inferior regions of the right septum was \( 22±5 \) mm, and of the left septum, \( 23±5 \) mm. From basket expansion, the width of the right and left septum was \( \approx 20 \) mm. A total of 17±3 electrodes were in contact with the right septum, and 19±2 electrodes were in contact with the left septum. Atrial capture, indicating electrode-septum contact, was obtained at a pacing threshold of 0.33±0.2 V on the right septum and 0.36±0.2 V on the left septum. Bipolar electrograms in the superoanterior right septum, computed from basket unipolar electrograms, consistently revealed His potentials as shown in Figure 3. The A-H interval was 60.2±3.5 ms, and the H-V interval was 31.5±2.7 ms.

In the initial 5 dogs, activation patterns of the septum were identical for pacing cycle lengths of 350 and 300 ms. Right and left septal activation times were also similar. During RV pacing, atrial activation was delayed during pacing at a cycle length of 300 ms compared with 350 ms. The following

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Figure 2. A, Surgical view of right septum. B, Surgical view of left septum. Both septal views illustrate sites of pacing investigated in study (*). Dashed black lines illustrate layout of basket splines against septum. Dashed white line borders extent of septum. SP indicates superoposterior; SM, superior middle; SA, superoanterior; IP, inferoposterior; IM, inferior middle; IA, inferoanterior; RPVO, right pulmonary vein ostium; LPVO, left pulmonary vein ostium; and BB, region of Bachmann’s bundle insertion.

Figure 3. Bipolar electrograms computed from unipolar electrograms recorded during sinus rhythm in superoanterior (SA), superior middle (SM), and superoposterior regions of right septum. Bipolar electrogram in SA region clearly depicts His potential (H) between atrial (A) and ventricular (V) potentials.

Figure 4. Simultaneous isochrone maps of RA and LA activation during 4 protocols. A, Sinus rhythm. B, RV pacing. C, Superior right septal pacing in middle aspect. D, Inferior right septal pacing in middle aspect. Each map is displayed on an unrolled rectangular grid of atrium as viewed by an observer from inside cavity. Activation times were determined from basket electrodes in anterior (A), lateral (L), posterior (P), and septal (S) aspects of atrium. Top and bottom correspond to superior and inferior regions of atrium, respectively. Earliest activation is represented by red, and latest by blue. Right and left aspects of septum are enclosed in dashed rectangles. Anatomic landmarks are illustrated on maps. IVC indicates inferior vena cava; MV, mitral valve; PVO, right inferior pulmonary vein ostium; SVC, superior vena cava; and TV, tricuspid valve annulus.
results are based on a pacing cycle length of 350 ms in all dogs.

**Septal Activation Pattern During Sinus Rhythm**
Simultaneous isochrone maps of RA and LA activation during sinus rhythm are shown in Figure 4A. During sinus rhythm, activation initiated in the superoposterior RA (consistent with the sinus node region). Activation of the right septum originated in the superoposterior region after 37±8 ms from onset of RA activation. The resulting wave front propagated inferiorly along the septum. Right septal activation was completed at 48±7 ms in the inferoanterior region.

Left septal activation initiated in the superior middle anterior region after 37±8 ms from onset of RA activation (17±7 ms later than the onset of right septal activation; P<0.001). This region corresponded with the insertion of Bachmann’s bundle in the left septum. Activation spread inferiorly along the left septum and was completed at 62±8 ms. In 3 dogs, a second early activation site appeared at 52±1 ms in the inferior left septum, from which the wave front propagated locally.

**Septal Activation Pattern During RV Pacing**
Representative simultaneous isochrone maps of RA and LA activation during RV pacing are shown in Figure 4B. During RV pacing, activation of the right septum initiated consistently in the inferoanterior region (corresponding to the atrioventricular node region). Earliest activation appeared after 150±26 ms from the pacing stimulus, and the ensuing wave front propagated along the right septum superiorly and posteriorly. In all dogs, right septal activation was completed in the superoanterior region at 170±28 ms.

Unlike the right septum, LA isochrone maps revealed 2 distinct and separate early activation regions on the left septum that appeared almost simultaneously in all dogs. One region originated in the superoanterior left septum at 163±27 ms and was generally more anterior to the region of earliest activation in the superior left septum during sinus rhythm. The ensuing wave front propagated inferiorly and posteriorly.

The second region emerged after 167±29 ms in the inferoanterior left septum (P=NS compared with the superior region), from which the wave front propagated superiorly and posteriorly. The left septum was activated predominantly by the superior wave front. The earliest left septal activation was 11±6 ms later than the onset of right septal activation (P=0.001). Activation was completed at 184±28 ms in the lower half of the left septum.

**Septal Activation Patterns During Superior Right Septal Pacing**
The superior right septum was paced in the anterior, middle, and posterior aspects, and simultaneous RA and LA isochrone maps were displayed as shown in Figure 4C. Patterns of activation of the right and left septum were similar for all 3 superior pacing sites. In 25 of 25 pacing protocols, 1 wave front originated in the superior right septum and propagated inferiorly along the septum. Activation of the right septum was completed after 37±6 ms from the pacing stimulus.

As in sinus rhythm, the left septum exhibited an early activation site in the superior region in all pacing protocols that emerged after 33±7 ms and was located in the superior middle anterior region. In addition, a second early activation site appeared in 13 of 25 protocols (5 dogs) in the inferior region at 40±5 ms (P=0.021 compared with the superior region). For pacing protocols resulting in a single superior wave front, left septal activation was completed in 56±8 ms. For pacing protocols resulting in 2 wave fronts, left septal activation was completed in 54±8 ms (P=NS), and activation of the left septum was dominated by the superior wave front.

**Septal Activation Patterns During Inferior Right Septal Pacing**
The inferior right septum was paced in the anterior, middle, and posterior aspects, and simultaneous RA and LA isochrone maps were plotted as shown in Figure 4D. Patterns of activation of the right and left septum were similar for all 3 inferior pacing sites. In 24 of 24 pacing protocols, activation of the right septum initiated from a single site in the inferior septum, and the ensuing wave front propagated superiorly. Right septal activation was commonly completed in the superoanterior region after 38±8 ms from the pacing stimulus.

As in RV pacing, 2 distinct and separate early activation sites appeared nearly simultaneously in both the superior and inferior left septum in all protocols. One wave front originated in the superior middle anterior left septum at 32±7 ms and propagated inferiorly. The second wave front originated in the inferior left septum at 32±8 ms and propagated superiority (P=NS compared with the superior region). The majority of the left septum was activated by the superior wave front. Activation was completed after 45±7 ms in the lower half of the left septum.

**Pacing-Site Dependence of Complete Activation Time of the Septum**
The time of completion of right septal activation is summarized in Figure 5 for all pacing sites. There were no significant differences between the pacing sites. The corresponding time of completion of left septal activation is also shown in Figure 5. Left septal activation was completed earlier during inferior right septal pacing than superior right septal pacing (P<0.001). Furthermore, during superior pacing, the anterior site resulted in a significantly longer time for completion of left septal activation compared with the middle site (P=0.016) and posterior site (P=0.007). Similarly, during inferior pacing, the anterior site resulted in a significantly longer time compared with the middle site (P=0.036) and posterior site (P=0.011).

**Right and Left Septal Electrograms**
Electrograms recorded simultaneously along the middle of the right septum and the left septum from the superior to inferior regions are shown in Figure 6 during sinus rhythm and in Figure 7 during inferior middle right septal pacing. During sinus rhythm, a single wave front was present on both
the right septum and the left septum; the left wave front was delayed compared with the right wave front. Both activation wave fronts propagated from the superior to inferior regions. During inferior right septal pacing, 1 wave front originated on the right septum and propagated from the inferior to superior region, whereas 2 wave fronts emerged on the left septum from both the superior and inferior regions that resulted in double potentials in the lower half of the left septum. Double potentials were observed in the middle to inferior left septum in the presence of 2 superior and inferior early activation wave fronts (Figure 7). Double potentials appeared during all RV pacing protocols and all inferior right septal pacing protocols. In addition, double potentials were recorded during sinus rhythm in 3 dogs and during superior right septal pacing in 5 dogs. A far-field effect in the inferior left septum was excluded on the basis of a mismatch in activation between the inferior right septum and inferior left septum. For example, during pacing in the inferior right septum, the earliest activation time that could be determined on the right septum within the vicinity of the pacing electrodes was 18±8 ms, which was significantly shorter than the earliest activation time in the inferior left septum (32±8 ms; P<0.001).

Figure 5. Complete activation times of right septum and left septum. Graphs are plotted as a function of site of pacing on right septum. *P=0.016; †P=0.007; ‡P=0.036; §P=0.011.

Figure 6. Simultaneous unipolar electrograms recorded during sinus rhythm from a basket spline along middle of right and left aspects of interatrial septum. Top electrogram corresponds to superior septum; bottom, to inferior septum. All electrograms are shown with respect to same reference.

Figure 7. Simultaneous unipolar electrograms recorded during inferior right septal pacing in middle region from a basket spline along middle of right and left aspects of interatrial septum. Top electrogram corresponds to superior septum; bottom, to inferior septum. All electrograms are shown with respect to same reference.
Discussion
For the first time, the right and left aspects of the interatrial septum were mapped at multiple sites simultaneously in the canine intact beating heart. Major findings of the study were that (1) activation of the right septum and the left septum was discordant and (2) electrical conduits were present between the RA and LA in the superior and inferior regions of the interatrial septum.

During sinus rhythm and right septal pacing in the superior region, activation of both the right septum and the left septum was initiated predominantly by a single wave front in the superior region that propagated inferiorly along the septum. However, there was a delay between the right septum and the left septum in onset as well as completion of activation. In some cases, a second wave front appeared in the inferior left septum. These results were in line with previous atrial mapping studies in which sinus rhythm activation was shown to spread rapidly along Bachmann’s bundle and enter the LA after a delay from RA activation. Previous epicardial mapping studies also demonstrated that RA sinus activation could cross the interatrial septum more slowly under the inferior vena cava. Recently, it was shown that the coronary sinus forms an electrical connection between the RA and LA. Whether conduction in the inferior septal region is through the coronary sinus and/or atrial tissue remains to be investigated.

Discordance in activation between the right and the left septum was further confirmed during RV pacing as well as right septal pacing in the inferior region. In both cases, a single wave front originated in the inferior right septum and propagated superiorly and posteriorly, whereas activation of the left septum was consistently caused by 2 distinct and separate wave fronts that propagated from the superior and inferior regions toward the middle of the septum. These results were consistent with an earlier observation on discordant activation of the septum during RV pacing.5

In the presence of 2 wave fronts on the left septum resulting from inferior right septal pacing, the majority of the left septum was activated by the superior wave front, whereas the inferior wave front resulted in limited local septal activation. Furthermore, the left septum completed its activation in a much shorter time than a single wave front resulting from superior right septal pacing. These findings suggested that (1) there was an electrical disconnection between the 2 sides of the interatrial septum and (2) electrical conduits linked the RA and LA in the superior septum and inferior septum. These observations agreed with separate embryological development of the right septum and the left septum. Furthermore, pacing in the anterior right septum resulted in a longer time for completion of left septal activation compared with middle or posterior pacing sites. This result suggested that electrical connections between the right and the left septum may be present in the posterior aspect.

The interatrial septum, providing the shortest distance between the sinus node and the atrioventricular node and the connection between the RA and LA, plays an important role in interatrial and intra-atrial conduction. Several studies previously examined the spread of activation through the intermodal atrial myocardium. The consensus excluded the presence of discrete tracts of specialized conduction tissue but supported the hypothesis that conduction occurred through the muscle bands along the atrial septum. Our study was not aimed at identifying the mechanism of conduction or the nature of cardiac fibers along the septum. However, during RV pacing, the activation wave front consistently propagated from the inferoanterior to the superoposterior region, and the latest activation was always in the superoposterior region. This observation suggested that a preferential pathway was present that permitted fast conduction from the inferior right septum to Bachmann’s bundle in the superior septum. This finding was consistent with the postulation that the observed preferential fast conduction along the right septum was due to faster spread of activation in a direction parallel to cardiac fibers than perpendicular to them; ie, anisotropy.

In the presence of 2 wave fronts propagating on the left septum from the superior and inferior regions, double potentials were always observed in electrograms recorded in the middle to inferior left septum. Electrograms recorded in the inferior left septum showed that activation in that region was primarily due to an inferior wave front. Electrograms recorded above that region showed a fusion of 2 activation wave fronts. The first potential was consistent with the inferior wave front, and the second potential was due to the superior wave front.

Clinical Implications
The interatrial septum may play an important role in the initiation and maintenance of atrial arrhythmias. The study demonstrated the presence of electrical connections in the superior and inferior septal regions, which in turn may furnish an anatomic pathway or substrate for reentry that can contribute to arrhythmias such as atypical atrial flutter and atrial fibrillation. Understanding these interatrial electrical connections may advance catheter ablation or pacing for managing complicated atrial arrhythmias.

Limitations
Our study has limitations. First, the shapes of the atria were complex, the right septum and the left septum were not at the same level, and the boundaries of the septum were not necessarily clear. For these reasons, some of the basket electrodes might have not been in contact with all atrial surfaces, which prevented us from completing all the pacing protocols in a few experiments. Second, at most 3 basket splines were in contact with each aspect of the septum. A greater number of electrodes would have provided higher resolution of activation details on the septum.

Conclusions
In dogs, activation of the right and left aspects of the interatrial septum is discordant. Both aspects of the septum are electrically disconnected for the most part, except in the superior (Bachmann’s bundle) region and in the inferior region.

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