Right Atrial Septal Electrode for Reducing the Atrial Defibrillation Threshold

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Background—The atrial defibrillation threshold (ADFT) energy of the standard lead configuration, right atrial appendage (RAA) to coronary sinus (CS), was reduced by >50% with the addition of a third electrode traversing the atrial septum in a previous study. This study determined whether the ADFT would be lowered by a more clinically practical third electrode placed in the right atrium along the atrial septum (RSP).

Methods and Results—Sustained atrial fibrillation was induced in 8 closed-chest sheep with burst pacing and maintained with pericardial infusion of acetyl-β-methylcholine chloride. A custom-made, dual-defibrillation catheter was placed with electrodes in the lateral RA, CS, and RSP. A separate defibrillation catheter was also placed in the RAA. ADFT characteristics of RAA→CS and 6 other single- or sequential-shock configurations were determined in random order by using biphasic, truncated-exponential waveforms in a multiple-reversal protocol. The delivered-energy, peak-voltage, and peak-current ADFTs for the sequential-shock configuration CS→RSP/RAA→RSP (0.53±0.31 J, 86±22 V, and 1.6±0.6 A, respectively) were significantly lower than those of RAA→CS (1.14±0.64 J, 157±34 V, and 2.5±1.1 A, respectively). The ADFT characteristics of RAA→CS and RA→CS were not significantly different, nor were those of CS→RSP/RA→RSP and CS→RSP/RAA→RSP.

Conclusions—The ADFT of the standard RAA→CS configuration may be markedly reduced with an additional electrode situated at the RSP. (Circulation. 2001;104:1066-1070.)

Key Words: defibrillation ▪ atrium ▪ electrophysiology

Patient acceptance of atrial defibrillation by an implantable device is limited by the discomfort to atrial defibrillation shocks.1-10 The standard lead configuration for atrial defibrillation, because of its simple electrode arrangement and low atrial defibrillation threshold (ADFT), is an electric discharge between electrodes in the right atrial appendage (RAA) and coronary sinus (CS).7,11 With this electrode configuration (RAA→CS), it has been demonstrated that after a failed shock near the ADFT, the recurrent atrial activation originates from the posterior left atrial wall near the pulmonary veins,12 a region distant from the defibrillation electrodes, where the shock potential gradient is low.13

In an effort to reduce the ADFT of the standard RAA→CS configuration, the benefit of an additional electrode situated across the interatrial septum (SP) was assessed in an earlier study.14 The delivered-energy ADFT of the configuration with the RAA and CS electrodes in common shocking to the SP electrode (RAA+CS→SP) was significantly lower than that of RAA→CS, and the configuration tested with the lowest mean ADFT was the sequential-shock configuration RAA→SP/CS→SP (first shock pathway/second shock pathway). Although these results were encouraging, long-term implantation of an electrode partly within the left atrium is undesirable because of the risk of thromboembolism. Therefore, in this study, we investigated the ADFT with an electrode wholly on the right side of the atrial septum (RSP).

Methods

The use of experimental animals in this study was approved by the institutional Animal Care and Use Committee at the University of Alabama at Birmingham. All studies were performed in accordance with the guidelines established in the Position of the American Heart Association on Research Animal Use, adopted by the American Heart Association on November 11, 1984.

Animal Preparation

Eight adult sheep (51±3 kg) were anesthetized with a 1:1 (vol/vol) mixture of tiletamine and zolazepam injected intramuscularly (8 to 10 mg/kg) followed 10 minutes later by a slow, intravenous bolus of 2 to 6 mg/kg thiopental. The animal was placed in a dorsally recumbent position on a fluoroscopy table, intubated, and ventilated (tidal volume 15 to 20 mL/kg) with a 4% isoflurane/O2 mixture at 8 to 12 breaths per minute. The isoflurane concentration was then decreased to 1.5% to 3.5% to maintain a deep surgical plane of anesthesia, and the ventilator settings were adjusted to maintain normal blood gas values. On the basis of serial blood analyses performed every 30 to 60 minutes, lactated Ringer’s solution

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supplemented with electrolytes was infused intravenously. The lead II ECG and arterial pressure were monitored continuously. The average sinus rate and P-R interval were recorded before and after the experimental protocol in each animal. Neuromuscular blockade was achieved with a 1 mg/kg succinylcholine chloride intravenous bolus followed by an intravenous drip (5 to 8 mg/min). After completion of the experiment, euthanasia was induced with an intravenous bolus of KCl.

Defibrillation Catheter Placement
We constructed a custom-made, dual-defibrillation catheter with 3 coils mounted on joined primary and secondary 6F catheters (Figure 1). Two 3-cm coil electrodes were mounted ~1 and 12 cm from the distal end of the primary catheter. A third 3-cm coil electrode was mounted 0.5 cm from the tip of the secondary catheter, which joined the primary catheter midway between its 2 coils. Through a jugular vein, this dual catheter was positioned with the distal electrode within the CS, the proximal electrode along the right atrial RA, and the electrode on the secondary catheter adjacent to the RSP (Figure 2). In addition, a modified quadripolar catheter (Mansfield EP-Boston Scientific Corp) with a bipolar pacing tip and a 3-cm coil electrode 1 cm from the tip was positioned in the RAA through the left femoral vein. A final catheter (Endotak DSP, Guidant Corp) with a pacing electrode at its distal end was positioned through the other jugular vein to the right ventricular apex.

Atrial Fibrillation and Defibrillation
To sustain atrial fibrillation (AF), acetyl-β-methylcholine chloride (Sigma Chemical Co) was continuously microinfused into the pericardial cavity through a 4F pigtail catheter at a rate of 0.08 to 0.40 (0.15±0.12) µg/min.14 Burst pacing of 2-ms stimuli delivered at 30- to 80-ms intervals through the RAA catheter was used to induce AF. AF was defined as irregular, rapid atrial activity with an average sinus rate and P-R interval were recorded before and after the completion of the protocol (103±7 versus 99±6 beats per minute, P>0.05). The lead II P-R intervals before and after completion of the protocol were also similar (149±16 vs 158±15 ms, P>0.05).

Once the administration level of acetyl-β-methylcholine chloride was sufficient to consistently maintain AF for >10 minutes, the defibrillation protocol was begun. A truncated-exponential waveform was produced by an external defibrillator (HVS-02, Ventritex, Inc.). This monophasic waveform was divided into 1 or 2 biphasic waveforms by high-voltage, cross-point switches.14 Each biphasic waveform had a first-phase duration of 3 ms and a second-phase duration of 1 ms. The interval between each phase of the biphasic waveforms and between the 2 biphasic waveforms of sequential shocks was 0.02 ms.

In each animal, the ADFTs of 7 test configurations (Table 1) were determined in a balanced-randomized order. Each ADFT was determined according to a multiple-reversal method with an initial peak voltage of 100 V. If the initial shock failed to defibrillate, the next and subsequent shock voltages were increased by 40 V until a shock succeeded. After the first shock that successfully terminated AF, the voltages of subsequent shocks were decreased by 20 V until a shock failed. Shock voltages were then increased by 10 V until a shock again succeeded. Conversely, if the initial shock successfully defibrillated, subsequent shock voltages were decreased by 40 V until a shock failed. Then shock voltages were increased by 20 V until a shock succeeded, after which shock voltages were decreased by 10 V until a shock failed. The last successful shock was deemed the ADFT shock for that configuration. From this shock, the peak-voltage, peak-current, and delivered-energy ADFTs were derived. Shocks were synchronized to be delivered 20 ms after the last of a set of 8 right ventricular pacing pulses, which were delivered at a cycle length of 250 to 400 ms.

Statistical Analysis
Results are expressed as mean±SD. Because some ADFT characteristics of some configurations exhibited nonnormality at a level <0.05,15 the effects of the 7 test configurations on each ADFT characteristic were tested by the nonparametric Friedman 2-way ANOVA (SPSS, version 6.0). A value of P<0.05 was considered significant.

Results
Sustained AF was induced in all animals. The average sinus rate at the beginning of the defibrillation protocol was not significantly different from that at the completion of the protocol (103±7 versus 99±6 beats per minute, P>0.05). The lead II P-R intervals before and after completion of the protocol were also similar (149±16 vs 158±15 ms, P>0.05). Except for isolated incidences of transient sinus bradycardia, no sinus arrest or atrioventricular dissociation occurred on atrial defibrillation. No incidences of spontaneous recurrence of AF after successful defibrillation shocks occurred.

Delivered-Energy ADFTs
The delivered-energy ADFTs of CS→RSP/RA→RSP and CS→RSP/RAA→RSP were significantly lower than those of each of the other 5 test configurations (Figure 3), except that the ADFT of CS→RSP/RA→RSP showed only a trend toward being lower than that of RA+RSP→CS. The ADFTs of RA+RSP→CS, RA→CS, RAA→CS, and RA→RSP/CS→RSP were not significantly different from each other. The ADFT of RA+CS→RSP was significantly greater than that of every other test configuration except for RA→RSP/CS→RSP and RAA→CS. The ADFT of CS→RSP/RA→RSP was 46±16% and 53±12% lower than those of RA→CS and RAA→CS, respectively, and that of CS→RSP/RAA→RSP was 55±12% lower than that of...
RAA→CS. The ADFT of RA→RSP/CS→RSP was 22±36% higher than that of RAA→CS.

**Peak-Voltage ADFTs**
The peak-voltage ADFTs of configurations CS→RSP/RA→RSP and CS→RSP/RAA→RSP, which were not significantly different from each other, were both significantly lower than those of the other 5 configurations (Figure 4), which in turn were not significantly different from each other. The ADFT of CS→RSP/RA→RSP was 42±9% and 45±7% lower than those of RA→CS and RAA→CS, respectively, and that of CS→RSP/RAA→RSP was 46±7% lower than that of RAA→CS.

**Peak-Current ADFTs**
The peak-current ADFTs of the test configurations from all of the animals are shown in Figure 5. Overall, these ADFTs fell into 3 zones, in which ADFTs within each zone were not significantly different from each other yet were significantly different from those of every configuration in the other 2 zones. The zone with the lowest peak-current ADFTs comprised the CS→RSP/RA→RSP and CS→RSP/RAA→RSP configurations; the middle zone was occupied by the RA+RSP→CS, RA→RSP/CS→RSP, RA→CS, and RAA→CS configurations; and RA+CS→RSP was the sole configuration in the highest zone.

**Pathway Impedances**
The impedances of the test configuration pathways are shown in the Table. The impedance of the CS→RSP current pathway was not significantly different, whether it was part of the RA→RSP/CS→RSP, CS→RSP/RA→RSP, or CS→RSP/RAA→RSP configuration. Likewise, the RA→RSP impedance was not significantly different whether it was part of the RA→RSP/CS→RSP or CS→RSP/RA→RSP configuration. The impedance of the RAA+CS→RSP current pathway was significantly lower than that of all other pathways tested. The impedance of RA+RSP→CS was significantly lower than that of pathways RA→CS, RAA→CS, and CS→RSP. The impedance of CS→RSP was significantly higher than that of RA→RSP and RAA→RSP, whereas the impedances between RA→RSP and RAA→RSP and between RA→CS and RAA→CS were not significantly different.

**Discussion**

**Primary Findings**
This study demonstrates that the ADFT of the standard lead configuration may be significantly reduced with the addition of an electrode within the RA placed along the SP. With all electrodes mounted on a custom-made, dual-defibrillation catheter, the delivered-energy, peak-voltage, and peak-current ADFTs for the sequential-shock configuration CS→RSP/RA→RSP were significantly lower than those of the standard configuration, RAA→CS (by 53±12%, 45±7%, and 37±10%, respectively). The ADFT characteristics of RAA→CS and RA→CS were not significantly different.
different, nor were those of CS→RSP/RA→RSP and CS→RSP/RAA→RSP.

Comparison With Previous Work

We previously reported an ADFT reduction with a 6-cm coil electrode that traversed the SP.14 With approximately two thirds of the electrode within the left atrium and one third within the RA, we found the delivered-energy ADFT of the sequential-shock configuration RAA→SP/CS→SP of 0.39±0.18 J to be significantly lower than that of the standard configuration, 1.27±0.67 J, a reduction of 68±8%. With the RA septal electrode tested in this investigation, the delivered-energy ADFT of RA→RSP/CS→RSP was 22±36% higher than that of RAA→CS. The likely reason for the marked difference in the efficacy of RA→(R)SP/CS→(R)SP in the 2 studies is that the transseptal electrode was primarily in the left atrium in the previous study, thereby causing the impedance between the RAA and SP electrodes to be significantly greater than that between the CS and SP electrodes. Therefore, in that study, the larger first component of the sequential shocks was delivered to the pathway with the higher impedance, so that the current across both pathways was more nearly equal than with the CS→SP/RAA→SP configuration. In the current study, the RSP electrode was entirely within the RA, so the impedance between the RA and RSP electrodes was significantly lower than that between the CS and RSP electrodes. Thus, with the RSP electrode, the larger first component of the sequential RA→RSP/CS→RSP shock was delivered across the lower impedance RA pathway, with the higher impedance pathway across the left atrium receiving the weaker second component of the sequential shock.

The configurations exhibiting the lowest ADFTs with the RSP electrode were those in which the left atrium experienced the first component of the sequential shock (CS→RSP) and the second component was delivered either through RAA→RSP or RA→RSP. Compared with the standard RAA→CS configuration, both of these configurations decreased the mean delivered-energy ADFT by >50%. Therefore, compared with the standard configuration, the reduction in delivered-energy ADFT of the lowest ADFT configuration tested with the RA septal electrode was similar to that tested with the transseptal electrode; however, the shock sequence was reversed.

In this investigation, the ADFTs of configurations that included the RAA electrode were not different from those analogous configurations with the RA electrode that was part of the custom-made, 3-electrode dual catheter. The CS→RSP/RAA→RSP and CS→RSP/RA→RSP delivered-energy ADFTs were 0.48±0.25 and 0.53±0.31 J, and those of RAA→CS and RA→CS were 1.14±0.64 and 0.98±0.44 J, respectively. Previous studies have reported differences in ADFTs for RA→CS configurations depending on the position of the RA electrode.8,9 In general, electrode positions within the appendage have been found to exhibit the lowest ADFTs, with lateral RA positions producing lower ADFTs than positions in the inferior RA. It is not clear why the ADFT of RAA→CS was not lower than that of RA→CS; perhaps the superolateral position of the RA electrode with
the dual catheter and the fact that the RA and RAA coils were somewhat shorter than those that have been tested previously account for this slight discrepancy.

Cooper and colleagues have reported ADFTs with sequential-shock configurations in a similar sheep model of AF. They reported that for an RAA→distal CS/pulmonary artery→proximal CS configuration, the delivered-energy ADFT of 0.36±0.13 J was significantly lower than that of the standard configuration, RAA→distal CS, 1.29±0.26 J. Although this 74% reduction in ADFT is greater than the 54% to 56% reduction with the RSP electrode, the configuration used by Cooper et al requires a catheter in the pulmonary artery, which is not required by the lowest ADFT configuration in this study.

Shock Discomfort
The discomfort associated with shocks represents 1 of the final hurdles of the clinical acceptance of ambulatory, device-based atrial defibrillation. Previous studies indicate that for shocks to be painless in a majority of patients, they need to be well below 1 J. The data also indicate that significant variation in patient discomfort is present, both within and across investigations. The significantly lower ADFT for the new electrode configuration tested in this study, although it is not below the pain threshold for all patients, may diminish discomfort for some patients. Furthermore, recent data suggest that the discomfort to defibrillation may be more closely related to the number of shocks required than to their amplitude and that patient satisfaction of the therapy is related to the therapy’s success. Therefore, 1 of the benefits of the use of a low-ADFT configuration may be the greater efficacy of defibrillation for a given shock strength, thus minimizing the need for multiple shocks. Testing of these possibilities will require clinical evaluation.

Dual-Defibrillation Catheter
This investigation tested a novel, custom-made, dual-defibrillation catheter. The catheter terminated as a standard CS defibrillation catheter, with its distal end within the CS. At its insertion into the CS ostium, however, the catheter bifurcated into 2 branches. One branch housed a coil defibrillation electrode along the lateral RA; the other branch housed a third defibrillation coil along the right side of the SP. Although the 2 branches were permanently affixed in our study, a more practical clinical implementation of such an electrode system might comprise a 2-catheter system, in which a CS catheter would be situated first and then the septal catheter would be placed by temporarily fastening it to a sheath that is then slipped over the CS catheter. Additionally, 1 or a pair of pace/sense electrodes could be mounted along this dual catheter to pace the left or right atrium. In this study, the sinus rate and P-R interval were not significantly altered by the defibrillation protocol; no sinus arrest or atrioventricular dissociation occurred due to multiple shocks. Thus, shocks delivered through the RSP electrode did not appear to detrimentally affect the specialized conduction system of the sheep.

Clinical Implications
One of the prime deterrents to the use of internal atrial defibrillation is the discomfort associated with the intensity of shocks required to successfully cardiovert AF. The low-ADFT electrode configuration described herein may decrease patient discomfort for at least 3 reasons: (1) AF may be converted with shocks of lesser magnitude; (2) at a particular shock strength, the lower ADFT should correspond to a greater likelihood of successful cardioversion, thus minimizing the necessity for multiple shocks, which have been shown to play a key role in patient discomfort; and (3) at a particular shock strength, the close spacing between the RSP electrode and either the RA or CS electrode should minimize the extracardiac shock field, thereby decreasing the stimulation of nerves and muscles.

Study Limitations
The present study was performed in sheep with acutely induced AF maintained with acetyl-β-methylcholine chloride. Therefore, the results cannot be extrapolated directly to patients with chronic AF.

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References
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