Linear Atrial Ablations in a Canine Model of Chronic Atrial Fibrillation

Morphological and Electrophysiological Observations

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Background—To test the hypothesis that susceptibility to sustained atrial fibrillation may be decreased by creation of linear atrial ablations, we established a canine model of chronic atrial fibrillation and used a novel catheter design to create atrial ablations.

Methods and Results—Chronic atrial fibrillation was induced in 16 dogs by creation of mitral regurgitation and rapid pacing of the atria. Temperature-controlled radiofrequency ablations were attempted along empirically derived, preselected atrial target sites in 11 dogs (ablation group), and a sham procedure was performed in 5 dogs (control group). Follow-up electrophysiology study and pathological examination were conducted 13 ± 5 days after the initial procedure. Immediately after ablation, sustained atrial fibrillation could be initiated in 1 of 9 surviving ablation dogs and 5 of 5 controls (P = 0.004). Four dogs died within 24 hours of the procedure. Permanent pacing was required in 4 dogs. At follow-up, 0 of 7 ablation dogs and 5 of 5 controls had atrial fibrillation (P = 0.001). Furthermore, 2 of 7 ablation dogs had sustained atrial tachycardias, one of which was successfully ablated. Pathological examination demonstrated frequent incomplete lesion sets and discontinuous lesions.

Conclusions—In this model, a reduction in the susceptibility to sustained atrial fibrillation can be achieved by long linear atrial ablations created with specially designed coil electrode catheters. Complete lesion continuity was not required to achieve a therapeutic effect. (Circulation. 1998;97:1176-1185.)

Key Words: catheter ablation ■ arrhythmia ■ atrium ■ electrophysiology ■ fibrillation

Atrial fibrillation is a common arrhythmia that is associated with an adverse long-term prognosis.1 The maze procedure was introduced in 1987 as a potentially curative operation for patients with symptomatic atrial fibrillation.2,3 A 98% early success rate has been reported with this technique,4 although the long-term outcome with regard to atrial mechanical function and thromboembolism is unknown. In addition, the maze procedure is a prolonged operation with significant morbidity resulting from the associated median sternotomy and cardiopulmonary bypass.

Atrial fibrillation ablation (the “catheter maze procedure”) is being conducted in human beings in medical centers in Europe and America on an investigational basis.5,6 Although these procedures are successful in eliminating or reducing atrial fibrillation in some patients, morphological lesion data are not available. As a result, little is known about the requisite number of lesions, the optimal lesion locations, or the necessity for continuous lesions. The purposes of the present study were (1) to determine whether an empirically derived set of atrial radiofrequency ablations could reduce the ability to sustain atrial fibrillation in dogs with chronic atrial fibrillation and (2) to determine whether lesion continuity predicted procedural efficacy.

Methods

All animal protocols were reviewed and approved by the Animal Research Committee at the University of Virginia Health Sciences Center, conformed to the guidelines published in the “Position of the American Heart Association on Research Animal Use,” and were conducted with the assistance/supervision of the Animal Resources Department veterinary staff.

Chronic Atrial Fibrillation Model

Sixteen female mongrel dogs weighing 25 to 50 kg were induced with ketamine (10 mg/kg) and diazepam (0.1 mg/kg), intubated, and maintained on a Harvard respirator pump with halothane (1% to 2%) or isoflurane (0.5% to 1.5%). Introducer sheaths were placed in the left femoral artery and vein. A flow-directed thermodilution end-hole catheter was advanced to the pulmonary artery, and a 59-cm 8F sheath was positioned in the left ventricle. Baseline hemodynamic measurements (pulmonary artery pressure, pulmonary capillary wedge pressure, left ventricular systolic pressure, heart rate, and cardiac output) were recorded. A 7F steerable catheter with a stiff 2-mm wire hook at its terminus was placed in the left ventricle and manipulated until a mitral chorda tendinea was ensnared. The catheter was then rapidly withdrawn to avulse the chorda. This procedure was repeated until the mean wedge pressure increased 5 mm Hg and/or obvious V waves appeared on the wedge pressure tracing. The catheters were removed and the wounds repaired.

The right neck and interscapular regions were steriley prepped and draped. An active-fixation atrial “J” permanent pacemaker lead

Received June 25, 1997; revision received October 14, 1997; accepted October 31, 1997.
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(Telecommunications Pacing Systems, Inc or Medtronic Inc) was introduced into the right jugular vein and advanced into the right atrial appendage. When adequate pacing parameters were obtained, the lead was connected to a specially modified Telecommunications unipolar implantable pulse generator (programmable rates from 120 to 640 bpm), and appropriate atrial pacing was confirmed. The wounds were repaired, and the animals were returned to the vivarium.

The pacemakers were programmed to a rate of 640 bpm and an output of two to three times atrial diastolic threshold for 6 weeks and then were reprogrammed to 120 bpm and subthreshold pacing outputs (1.2 mV, 0.125 ms). After 24 hours at subthreshold and reduced-rate pacing, an ECG was obtained to verify the presence of atrial fibrillation. If atrial fibrillation was not present, the pacemaker was reprogrammed to its previous values, and testing was repeated at 1- to 2-week intervals. If atrial fibrillation was present, the dog was observed for a minimum duration of 1 week. A 24-hour ambulatory ECG recording was obtained (SpaceLabs Inc) to confirm sustained atrial fibrillation.

Electrophysiological Testing
Before testing, all dogs had two-dimensional echocardiography to evaluate left atrial size. Electrophysiological testing was performed in both the ablation group and the control group. The permanent pacemaker was explanted before electrophysiological testing in all animals. The femoral vessels were cannulated, and a 64-pole basket electrode catheter (EP Technologies, Inc) was placed in the atria for recording and pacing. Thirty-two bipolar electrograms (30 to 500 Hz; interpolar distance, 0.5 cm) were displayed and recorded with a Bard EP System (Bard/USCI). Before ablation, electrical cardioversion of atrial fibrillation was attempted in all animals. In animals that were successfully converted to sinus rhythm, atrial programmed stimulation was performed at twice atrial diastolic threshold through a basket catheter bipole positioned in the high right atrium at a site with a pacing threshold <1 mA. Single, double, and triple atrial stimuli were delivered after an 8-beat paced drive at 350 ms, followed by high-output (10 mA) rapid atrial pacing for a duration of up to 15 seconds until 2:1 atrial exit block was reached. The extrastimulus coupling intervals were shortened by 10-ms intervals until atrial refactoriness was reached.

Local atrial interelectrogram intervals were measured with electronic calipers at each bipole in each animal. The local atrial fibrillation cycle length was calculated as the mean of 25 consecutive FF intervals at each bipole. Mean atrial fibrillation cycle length was calculated as the mean of the local atrial fibrillation cycle length values within an entire atrium. Mean atrial fibrillation cycle length was calculated for three conditions: at baseline (before cardioversion during the initial ablation procedure); after right atrial lesion formation; and after left atrial lesion formation.

Radiofrequency Catheter Ablation System
Atrial fibrillation ablation was conducted with a variety of specialized catheters (EP Technologies; Fig 1). All catheters were 8F and were composed of a series of coil electrodes made from stainless steel or gold that measured 12 to 18 mm long and had 30- to 50-mm interelectrode spacing. To investigate the effect of the temperature-monitoring mechanism on lesion-related char formation, two electrode coil designs were used. One design consisted of catheters that had a single thermistor embedded at the midpoint of the electrode for temperature monitoring and temperature-feedback power control. The second design consisted of catheters that had two thermocouples located at opposite ends of each coil and 180° opposite one another in the cross-sectional plane. The higher of the two recorded temperatures (the thermocouple positioned toward the electrode-tissue interface) was used for temperature-feedback power control. The catheter configuration was curvilinear; a variety of curve radii and interelectrode spacing. To investigate the effect of the temperature-monitoring and temperature-feedback power control. The second design consisted of catheters that had two thermocouples were first created in the right atrium. Catheters were positioned by creation of loops with the distal portion of the catheter and subsequent release of the catheter curve to maximize longitudinal contact of the catheter body with the atrial wall. Lesions were first attempted in the right atrium along the following target lines (Fig 2A): an intercaval lesion extending from the superior to inferior vena cava in the posterolateral atrium; a lesion across the isthmus between the tricuspid annulus and inferior vena cava; and a line from the sinus node region anteriorly, extending along the anterolateral base of the atrial appendage and intersecting the tricuspid valve orifice. The goal of this lesion set was to establish a line of conduction block between the superior and inferior venae cavae and to compartmentalize the right atrial free wall by establishing lines of conduction block between the superior vena cava and the anterior border of the tricuspid valve annulus, between the inferior vena cava and the inferior border of the tricuspid valve annulus, and between the superior vena cava and the inferior vena cava. In four cases, lesions were placed from the midseptal region superiorly, intersecting with the anterior ablation line, but this lesion was discontinued because of the high incidence of associated complete heart block (see “Results” section). Lesions were then created in the left atria as follows (Fig 2B): an inferoposterior transverse line from the left atrial appendage to the right interappendicular left atrial region, an anterosuperior transverse line from the appendage to the anterior portion of the atrial septum, a lateral vertical line from the mitral annulus to the
appendage, a posterior vertical line from the mitral annulus intersecting the interposterior transverse lesions, and an anterior vertical line from the mitral annulus intersecting the anterosuperior lesions. The goal of this lesion set was (1) to bisect the left atrium into a superior and an inferior portion by creating two lesions, one from the left atrial appendage toward septum and vertical lines from left atrial appendage toward septum and vertical lesions on lateral (3), posterior (4), and anterior (5) walls extending to mitral annulus. See text for further details.

Ablation attempts to create a given target line were terminated when the operator was satisfied that a given ablation line had been completed (on the basis of catheter position, lesion location, and mean temperature during lesion formation). Once a series of lesions in a target line was begun, the first lesion was attempted when the operator felt that the catheter was in the appropriate position on the basis of fluoroscopic imaging. Radiofrequency current was then applied for 60 seconds. If the preset temperature was achieved, the next lesion in the target line was attempted. If the preset temperature was not achieved (presumably due to poor tissue contact), the catheter was manipulated until an adequate temperature could be achieved. This process was repeated until the target line was completed. Assessment of tissue contact was based solely on the ability to achieve adequate heating without abrupt changes in impedance. If atrial fibrillation or atrial reentrant tachycardia persisted or could be reinitiated after completion of all proposed lesions, mapping was performed with either the multielectrode basket catheter or a roving quadripolar electrode catheter. If discrete high-frequency middiastolic potentials were identified during atrial tachycardia, then additional focal radiofrequency lesions were placed at that site. If no appropriate sites for ablation were identified, then the procedure was terminated.

After termination of atrial fibrillation with ablative lesions, postablation testing was conducted. If no sustained atrial fibrillation or atrial tachycardia could be initiated with up to triple atrial extrastimuli and high-rate atrial pacing from both left and right atrial pacing sites, then the procedure was terminated. If sustained tachycardia could be induced, further mapping and ablation were attempted. The total procedure duration was limited to 10 hours. If there was evidence of significant sinus node dysfunction or atrioventricular block after an apparently successful ablation, a permanent pacemaker was implanted and programmed to a demand rate of 70 bpm.

**Control Procedure**

A sham ablation procedure was conducted in 5 dogs. After chronic atrial fibrillation was established, the control dogs were anesthetized, femoral vessels were cannulated, and transseptal catheterization was performed. After 90 minutes of sustained atrial fibrillation, cardioversion was attempted, programmed stimulation was performed, and sinus rhythm was restored. The animals were monitored in sinus rhythm for 4 hours. At that time, electrophysiological testing was repeated to determine further susceptibility to sustained atrial fibrillation. If atrial fibrillation was initiated, the animals were again cardioverted. At the conclusion of the control study, the wounds were repaired, and the animals were returned to the vivarium in sinus rhythm.

**Follow-up Testing**

Animals in both the ablation group and the control group underwent follow-up testing. General anesthesia was administered, the femoral
vessels were cannulated, and transseptal catheterization was performed. If animals were in sinus rhythm, programmed atrial stimulation and rapid atrial pacing were performed as described above. If an atrial tachycardia could be initiated, intra-atrial electrogams were recorded throughout both atria in an attempt to identify middiastolic potentials. If they were identified, limited focal ablations were applied to these regions in animals from the ablation group in an attempt to terminate these rhythms. At the conclusion of the procedure, the animals were euthanized with an overdose of pentobarbital, and the hearts were rapidly explanted for pathological examination.

Pathological Examination
Explanted hearts were examined grossly for evidence of pericardial inflammation and transmural extent of ablation lesions. The left and right atria were opened, and the lesions were identified. The location, length, and width of each lesion were recorded. Each lesion was bisected longitudinally and stained with the histochemical dye nitroblue tetrazolium (0.5 mg/mL, 0.2 mol/L Sorensen’s buffer) to demarcate viable from nonviable myocardium. The transmural extent of the lesion was recorded. The endocardial surface areas of the left and right atria were planimetered, and the relative lesion area versus the total endocardial surface area was calculated. The lesions were classified by degree of continuity and location relative to the targeted line. If there was any visible macroscopic lesion, it was designated as such. If there was a transmural continuous lesion that spanned >50% of the targeted region, it was defined as a partial lesion. A transmural continuous lesion that spanned the entire targeted region was defined as a complete lesion. To assess the targeting capabilities of the operator, the targeting was defined as accurate if there were visible lesions located in the targeted anatomic region and inaccurate if there were no visible lesions in the targeted region.

Statistical Analysis
Hemodynamic and clinical data were stored in a master computer file. All ECG and electrogram data were stored on optical disk for later retrieval and analysis. Statistical analysis was conducted with RS/1 (BBN Software Inc.). Continuous data were expressed as mean±SD. Comparisons of continuous variables among groups were performed with a two-way ANOVA. Paired comparisons among conditions were performed with two-tailed, paired Student’s *t* tests for normally distributed data or Mann-Whitney tests for skewed data. Categorical data were analyzed with Fisher’s exact tests. Regression lines were determined by least-squares analysis. Statistical significance was defined as *P*<0.05.

Results
Preablation Electrophysiological Evaluation
A summary of the rhythm characteristics of each animal in both the ablation group and the control group is displayed in Table 1. Before testing and/or ablation, all animals demonstrated atrial fibrillation during the entire 24-hour period of ambulatory ECG monitoring. On the day of testing, 10 of 11 dogs in the ablation group and 5 of 5 dogs in the control group were in sustained atrial fibrillation (*P*=NS). The remaining dog in the ablation group had nonsustained atrial fibrillation 2 to 24 minutes in duration initiated with atrial extrastimuli. Electrical conversion to sinus rhythm was successful in 8 of the 10 dogs in the ablation group with sustained atrial fibrillation and 5 of 5 control dogs (*P*=NS). Two dogs in the ablation group immediately reverted to atrial fibrillation within 2 seconds after each of two shocks; therefore, programmed stimulation was performed only in 9 dogs in the ablation group in whom sinus rhythm could be maintained. Of dogs that could be cardioverted, sustained atrial fibrillation lasting ≥30 minutes could be initiated in 8 of 9 dogs with single or double atrial extrastimuli in the ablation group and 5 of 5 dogs in the control group (*P*=NS).

Atrial Fibrillation Ablation
The mean initial procedure duration was 8.1±2.1 hours in the ablation group and 9.4±1.8 hours in the control group (*P*=NS). A total of 49±19 radiofrequency energy deliveries (range, 38 to 102) were used to create lesions along 7.5±1.2 targeted lines. The mean delivered power was 60±40 W, which resulted in a mean recorded temperature of 64°±9°C. Despite a preset target temperature of 70°C, 37 of 359 ablations (10%) performed with the single-thermistor electrodes showed evidence of coagulum and char adhering to the electrode. Of the lesions created by electrodes with dual temperature sensors, 2 of 244 ablations (1%) showed evidence of adherent coagulum or char (*P*=0.001) despite routine use of a preset 80°C temperature. The mean recorded temperature was 68.1±5.8°C for the dual-thermocouple electrodes and 59.7±9.3°C for the single-thermistor electrodes (*P*<0.001). When char was observed, both single- and dual-thermistor electrodes were associated with char formation at the terminal portion of the coils. Lesion discontinuity occurred in regions of poor tissue contact for both electrode types. In addition, electrodes with dual thermocouples occasionally demonstrated midcoil discontinuity.

A total of 32±11 lesions were created along 3.5±0.7 targeted lines in the right atrium, and 37±17 lesions were created along 4.0±1.0 targeted lines in the left atrium. In four cases, additional lesions (mean, 3.75 per dog; range, 2 to 6) were required to terminate atrial arrhythmias. These lesions were delivered to sites demonstrating middiastolic electrical activity. The location of these lesions included the inferior vena cava–tricuspid valve isthmus region, the lateral right atrium, the right atrial septal region, the right pulmonary vein region of the left atrium, the anterior left atrial free wall, and the posterior mitral valve annulus. Forty-four of 64 lesions (69%) made with single-thermistor electrodes and 29 of 55 lesions (53%) made with dual-thermocouple electrodes were continuous (*P*=0.9).

The rhythm outcomes of the initial and follow-up procedures are presented in Table 2. In the ablation group, 2 dogs died during the ablation procedure and 2 died within 24 hours of the procedure. One intraoperative and one early postoperative death were attributable to unrecognized hypothermia that progressed through the prolonged procedure, leading to decreased clearing of anesthetic agents and probable anesthesia overdose. A death that occurred 1 hour after the procedure was unexplained but was associated with hypoxemia and a profound respiratory and metabolic acidosis before cardiac arrest, suggesting aspiration or another anesthesia-related complication. The second acute death occurred several minutes after completion of a radiofrequency lesion and was the result of an episode of sudden-onset ventricular fibrillation from which the dog could not be resuscitated. No dogs in the control group died (*P*=.24 compared with ablation group).
After completion of the predetermined lesions, sustained atrial fibrillation could still be initiated by programmed stimulation in only 1 of 9 surviving dogs from the ablation
group and 5 of 5 dogs from the control group (P=.004). Sustained atrial tachycardia could be initiated in 3 of 9 surviving dogs after ablation and in 0 of 5 controls (P=.26).

In the ablation group, 4 dogs required implantation of a permanent pacemaker after ablation, 2 for complete heart block due to the midseptal lesion and 2 for sinus bradycardia. No dog had termination of atrial fibrillation without left atrial ablations.

**Follow-up Testing**

Electrophysiological testing was performed at 13±5 days after the baseline ablation procedure. All 7 surviving ablation dogs had sinus rhythm as the initial rhythm, whereas 2 of 5 controls had atrial fibrillation as the initial rhythm at follow-up study and the remainder had sinus rhythm. Programmed atrial stimulation resulted in the initiation of sustained atrial fibrillation in 0 of 7 ablation dogs and 5 of 5 control dogs (P=.001). Atrial stimulation resulted in sustained atrial tachycardia in 2 of 7 ablation dogs and 1 of 5 control dogs (P=NS). In one of the ablation group dogs with sustained atrial tachycardia, a discrete site of middiastolic activity was identified with mapping, and ablation at that site terminated the arrhythmia, after which no further tachycardia could be initiated (Fig 3). Three of the ablation group dogs had nonsustained atrial tachycardia in response to atrial programmed stimulation (cycle lengths, 300, 279, and 195 ms; all 2 minutes in duration). In only 1 of 7 ablation group animals could any sustained atrial tachyarrhythmia be initiated at

**Figure 3.** Example of atrial tachycardia that occurred after right and left atrial linear ablations. Displayed from top to bottom are surface ECG leads I, II, and aVF and eight intra-atrial electrograms recorded from two bipolar pairs on each of four basket electrode splines. Middiastolic potentials (arrows) are seen in electrogram 4−3. Ablation at that site with a 10-mm-tip catheter eliminated tachycardia. See text for further details.

**TABLE 2. Atrial Fibrillation Ablation Results**

<table>
<thead>
<tr>
<th>Initial Study</th>
<th>Follow-up Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. RA RF</td>
<td>No. LA RF</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Ablation group</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>AF</td>
</tr>
<tr>
<td>2</td>
<td>AF</td>
</tr>
<tr>
<td>3</td>
<td>AF</td>
</tr>
<tr>
<td>4</td>
<td>AF</td>
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<tr>
<td>5</td>
<td>AF</td>
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<tr>
<td>6</td>
<td>SR</td>
</tr>
<tr>
<td>7</td>
<td>AF</td>
</tr>
<tr>
<td>8</td>
<td>AF</td>
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<tr>
<td>9</td>
<td>AF</td>
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<td>10</td>
<td>AF</td>
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<tr>
<td>11</td>
<td>AF</td>
</tr>
<tr>
<td>Control group</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>AF</td>
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<tr>
<td>2</td>
<td>AF</td>
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<td>3</td>
<td>AF</td>
</tr>
<tr>
<td>4</td>
<td>AF</td>
</tr>
<tr>
<td>5</td>
<td>AF</td>
</tr>
</tbody>
</table>

No. RA RF indicates No. of applications of radiofrequency energy in the right atrium; No. LA RF, No. of applications of radiofrequency energy in the left atrium; AF, atrial fibrillation; AT, atrial tachycardia; PES, programmed electrical stimulation; and SR, sinus rhythm.

Survived procedure but died within 24 hours; †died during procedure; ‡nonsustained episodes of atrial fibrillation 2 to 24 minutes in duration initiated with extrastimuli.

**TABLE 3. Atrial Fibrillation Cycle Lengths**

<table>
<thead>
<tr>
<th></th>
<th>Baseline, ms</th>
<th>Post RA Lesions, ms</th>
<th>Post RA and LA Lesions, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>109±16</td>
<td>122±18*</td>
<td>155±19f</td>
</tr>
<tr>
<td>LA</td>
<td>94±6</td>
<td>105±17</td>
<td>147±28*</td>
</tr>
</tbody>
</table>

RA indicates right atrium; LA, left atrium.

*P<.05 vs baseline; †P<.01 vs baseline.
the end of the follow-up procedure, compared with 5 of 5 control group animals (4 with atrial fibrillation, 1 with atrial tachycardia; \( P = 0.015 \)).

Characteristics of Atrial Tachycardias
Several observations regarding the atrial tachycardias that occurred during the initial ablation and at follow-up were made. In the ablation group, these tachycardias could all be initiated and terminated with programmed atrial stimulation. The surface ECG P-wave morphologies and the intra-atrial activation sequences were not consistent with typical type 1 atrial flutter. In addition, these regular atrial tachycardias were never observed until after left atrial ablations were created. In the control group, the one observed atrial tachycardia could be initiated with either rapid atrial pacing or programmed atrial extrastimuli. In contrast to the ablation dogs, the atrial tachycardia in this dog could not be terminated with pacing, suggesting the possibility of an automatic mechanism in that case. As with the ablation dogs, the surface P-wave morphologies and the intra-atrial activation sequences were not consistent with typical type 1 atrial flutter.

Table 3 contains the mean atrial fibrillation cycle length values for each atrium at baseline, after right atrial ablation, and after left atrial ablation. Right atrial lesions alone prolonged right atrial fibrillation cycle length but had little effect on left atrial fibrillation cycle lengths; however, left atrial lesions combined with right atrial lesions resulted in a significant prolongation of both right and left atrial fibrillation cycle lengths (Fig 4).

Pathological Findings
Gross examination of the explanted hearts showed multiple areas of atrial subepicardial coagulation and hemorrhage. The animal that had a ventricular fibrillation cardiac arrest during the procedure had gross evidence of coagulum that had embolized to the mid left anterior descending coronary artery and to a large diagonal branch (Fig 5). Multiple left and right atrial lesions were present on the atrial epicardial and endocardial surfaces. Lesion extent, continuity, accuracy, and number of ablations per target line are presented in Table 4. Despite efforts to create continuous lesions at the targeted sites, discontinuous lesions were common, particularly in the left atrium. When continuity was not observed in the linear lesion, it was most frequently the result of failure of lesion production from one or more individual electrodes or partial
lesion formation with central or end-of-lesion dropout at individual electrodes. The regions of maximal lesion continuity corresponded with the sites of most stable catheter positioning. The total endocardial surface area of the right atrial ablative lesions was 1000±461 mm$^2$, which represented 22±9% of the right atrial endocardial surface. Similarly, the total endocardial surface area of the left atrial ablative lesions was 840±306 mm$^2$, which represented 20±4% of the left atrial endocardial surface.

**Predictors of Procedure Success**

Acute procedure success (no sustained atrial tachyarrhythmias after ablation) was achieved in 4 of 9 animals that survived the acute procedure. Table 5 contains data on predictors of procedural success. Animals in whom atrial fibrillation ablation was not successful in the initial procedure had a longer duration of spontaneous sustained atrial fibrillation before undergoing ablation than those in whom the procedure was acutely successful. Furthermore, because lesion formation was discontinued if atrial fibrillation ablation was acutely successful, it is not unexpected that those cases with ablation failure underwent a larger number of radiofrequency energy deliveries than cases of ablation success.

**Discussion**

The present study demonstrated that multiple-coil, temperature-feedback ablation catheters can be used to create atrial ablations that reduce further susceptibility to atrial fibrillation compared with control animals. Procedure success was more likely in animals with a shorter duration of antecedent atrial fibrillation, an observation that parallels those made in patients who have undergone the surgical maze procedure. Despite the efficacy of these ablations in controlling atrial fibrillation, the procedure was associated with significant morbidity and mortality, some of which was undoubtedly related to char formation at an ablation site. Furthermore, the creation of atrial ablations was associated with atrial tachycardia at follow-up, an observation that parallels those made in patients who have undergone the surgical maze procedure. In one case, the atrial tachycardia was successfully ablated during the follow-up procedure. The main pathological findings were that, in some cases, the ablation procedure could be effective without completion of the entire lesion set and that the procedure could be effective despite a high prevalence of pathologically discontinuous lesions.

**Comparison With Previous Studies**

The reported success rates of the surgical maze procedure have ranged from 84% to 98%. Perioperative complications have included death (1.3%), need for permanent pacing (40%), and delayed recovery of atrial mechanical function.

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### Table 4. Findings at Pathological Examination vs Anatomic Region Targeted

<table>
<thead>
<tr>
<th>Targeted Region</th>
<th>Any Lesion</th>
<th>Partial (&lt;50%)</th>
<th>Complete (100%)</th>
<th>Targeting Accuracy, %</th>
<th>No. Ablations Per Target Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right atrium</td>
<td>100</td>
<td>91</td>
<td>82</td>
<td>100</td>
<td>12±5</td>
</tr>
<tr>
<td>Intercaval</td>
<td>91</td>
<td>45</td>
<td>0</td>
<td>73</td>
<td>14±6</td>
</tr>
<tr>
<td>TV-IVC isthmus</td>
<td>100</td>
<td>64</td>
<td>27</td>
<td>82</td>
<td>6±3</td>
</tr>
<tr>
<td>Lateral vertical</td>
<td>91</td>
<td>45</td>
<td>36</td>
<td>73</td>
<td>9±4</td>
</tr>
<tr>
<td>Posterior vertical</td>
<td>18</td>
<td>9</td>
<td>0</td>
<td>9</td>
<td>7±3</td>
</tr>
<tr>
<td>Anterior vertical</td>
<td>63</td>
<td>54</td>
<td>9</td>
<td>6</td>
<td>6±3</td>
</tr>
</tbody>
</table>

Any lesion indicates transmural lesions of any dimensions observed in the targeted region; partial, transmural continuous lesion spanning >50% of the targeted region; complete, transmural continuous lesion spanning the entire targeted region; targeting accuracy, observed lesions located in anatomic region targeted fluoroscopically at the time of the ablation procedure; TV, tricuspid valve; and IVC, inferior vena cava.

### Table 5. Predictors of Procedural Success

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Unsuccessful</th>
<th>Successful</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left atrial size, cm</td>
<td>3.3±0.5</td>
<td>3.8±0.1</td>
<td>NS</td>
</tr>
<tr>
<td>Mean radiofrequency power, W</td>
<td>61±9</td>
<td>58±3</td>
<td>NS</td>
</tr>
<tr>
<td>Mean temperature, °C</td>
<td>64±7</td>
<td>59±3</td>
<td>NS</td>
</tr>
<tr>
<td>No. of attempted target ablation lines</td>
<td>7.8±1.5</td>
<td>7.0±1.2</td>
<td>NS</td>
</tr>
<tr>
<td>No. of lesions at necropsy</td>
<td>11.0±3.2</td>
<td>9.5±5.1</td>
<td>NS</td>
</tr>
<tr>
<td>No. of target lines with lesions</td>
<td>5.8±1.1</td>
<td>5.5±0.6</td>
<td>NS</td>
</tr>
<tr>
<td>Total ablated endocardial surface, mm$^2$</td>
<td>1779±188</td>
<td>1761±765</td>
<td>NS</td>
</tr>
<tr>
<td>Preablation atrial effective refractory period, ms</td>
<td>117±6</td>
<td>117±12</td>
<td>NS</td>
</tr>
<tr>
<td>Preablation mean atrial fibrillation cycle length, ms</td>
<td>104±12</td>
<td>119±21</td>
<td>NS</td>
</tr>
<tr>
<td>Atrial fibrillation duration, d</td>
<td>32±20</td>
<td>8±2</td>
<td>.057</td>
</tr>
<tr>
<td>No. of total radiofrequency energy deliveries</td>
<td>84±15</td>
<td>59±4</td>
<td>.018</td>
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Failure of the procedure has been associated with a longer antecedent duration of atrial fibrillation and a larger left atrial size.\(^9\) Because the maze procedure requires prolonged cardiopulmonary bypass, attempts have been made to design a simplified procedure.\(^9\)

As catheter ablation techniques have evolved, it has been proposed that selected patients with atrial fibrillation might benefit from this therapy. Haitzinger et al.\(^7\) conducted atrial fibrillation ablation in 45 patients with paroxysmal atrial fibrillation. One subset of patients responded to right atrial ablations with a reduction in the number and/or duration of episodes, whereas another subset required repeat ablations in the right and/or left atria. These authors concluded that radiofrequency catheter ablation of paroxysmal atrial fibrillation is possible and that left atrial lesions combined with right atrial lesions are more effective than right atrial lesions alone. Swartz et al.\(^9\) presented similar findings.

Animal Model
The degree to which data obtained in this canine model can be generalized to human atrial fibrillation is an important issue. The presence of mitral regurgitation results in several physiological phenomena that favor sustained atrial fibrillation: left atrial volume and pressure overload, reduced atrial effective refractory period, and increased left atrial surface area. Although chronic pacing can establish sustained atrial fibrillation in the absence of mitral regurgitation, the duration of this atrial fibrillation after discontinuation of pacing is unknown. In addition, because rapid atrial pacing often results in rapid ventricular rates, the atrial fibrillation induced by atrial pacing alone actually occurs as a result of a combination of atrial pacing and tachycardia-related ventricular myopathy. Because the purpose of this investigation was to determine whether creation of linear atrial ablations could eliminate atrial fibrillation, mitral regurgitation was combined with rapid atrial pacing to maximize the ability to achieve chronic, sustained atrial fibrillation. Although there may be several differences between the atrial fibrillation in the present canine model and human atrial fibrillation observed in the clinical setting, several observations suggest that this model may adequately represent some types of human atrial fibrillation. As in the present canine model, left atrial volume and/or pressure overload contributes to a significant subset of human atrial fibrillation, including that associated with hypertension, mitral valve disease, or left ventricular systolic and/or diastolic dysfunction. After cardioversion, spontaneous recurrences of atrial fibrillation occurred in 2 of 5 control animals. Atrial fibrillation was easily reinitiated in most study animals with single atrial premature beats and was refractory to cardioversion in 2 animals. Furthermore, animals with short-duration atrial fibrillation were more likely to respond to ablative therapy than counterparts with longer-duration atrial fibrillation, an observation that parallels those in patients with atrial fibrillation who have undergone ablation.

Clinical Implications
Although initial clinical reports of catheter ablation of atrial fibrillation are promising, these reports contain no data on lesion pathology. In addition, there appears to be a high prevalence of atrial tachycardia at follow-up. Data from the present study have several implications relevant to the evolution of catheter ablation for atrial fibrillation.

Safety
Procedure-related morbidity and mortality are major concerns in the development of ablation as a treatment for atrial fibrillation. In the present study, one death was a direct result of ablation-associated char that embolized to the left anterior descending coronary artery in one animal. In addition, the char formation (compared with dual-thermocouple electrodes) despite the lower target temperatures and detected temperatures with these catheters. The most likely explanation for this observation is that the temperature recorded by the single-thermistor electrodes underestimates the peak temperature at the electrode/tissue interface compared with dual-thermocouple electrodes. This phenomenon can be explained by the “edge effect,” which states that radiated energy is concentrated at sharp geometric gradients.\(^10\) To minimize char formation, future generations of multielectrode catheters should contain dual temperature sensors and target temperatures should be limited to those required for adequate lesion formation. Systemic heparin therapy should be administered during these ablation procedures in an attempt to minimize thrombus formation. In addition, efforts to limit the ablated atrial surface area may decrease the incidence of thromboembolism. This may be accomplished by limiting lesion number and width.

Other procedure-related complications were respiratory distress syndrome and complete heart block. Prolonged general anesthesia can be associated with the adult respiratory distress syndrome and was probably the cause of the respiratory failure observed during this investigation. Efforts to avoid or limit general anesthesia duration during ablation should be made. Complete heart block was due to lesion formation in the right atrial midseptal region in both cases and was not observed after this lesion was abandoned. Midseptal lesion formation might be attempted only as a last resort, if at all, to minimize the incidence of this complication.

Lesion Continuity
Possible explanations for poor lesion continuity observed during this investigation include poor targeting by the operator, poor tissue contact due to endocardial ridges, or current inhomogeneity due to the edge-effect phenomenon. Single-thermistor electrodes had a higher rate of impedance rise and char formation than did dual-thermocouple catheters; however, the proportion of continuous lesions was not significantly different between the two design types. Discontinuous lesion segments were in regions of poor tissue contact for both design types; in addition, dual-thermocouple catheters occasionally demonstrated midcoil discontinuity. The improved detection of edge temperatures with dual-thermocouple catheters resulted in less char formation. However, given the length of the coils, the center portion may have achieved less tissue heating and therefore may have accounted for the occasional occurrence of lesion discontinuity in the midpor-
tion of the coil. Because the proportion of discontinuous lesions did not differ significantly between design types, the possibility that the electrode lengths were too long and therefore resulted in inhomogeneous energy transfer along the length of the electrodes should be carefully considered.

Correlation of ablation data and lesion location suggests that the number of lesions required per target line is a function of the length of the target line, the ease of positioning the catheter in that location, and the ability to achieve adequate contact at that location. The relatively high number of attempted radiofrequency ablations per targeted line is a reflection of multiple overlapping catheter positions and inadequate energy deliveries due to poor electrode-tissue contact. The fact that procedure success occurred despite lack of continuity of some lesions suggests that continuous lesions may not be required to successfully ablate atrial fibrillation. Furthermore, given the efficacy of ablation in preventing atrial fibrillation and the marked differences between the ablation target lines used in the present investigation versus the suture lines used in the maze procedure, one can conclude that multiple combinations of ablations may be successful in terminating atrial fibrillation and that catheter-based approaches need not recreate the entire maze procedure. There was no difference between the successful and unsuccessful groups with regard to the number of endocardial lesions or the endocardial surface area ablated. The high prevalence of atrial tachycardias may be a result of the high degree of lesion discontinuity. The most rational developmental step in the evolution of this procedure would be to improve the continuity of the left atrial lesions, possibly by changes in the ablation electrode geometry and by use of new catheter designs such as deployable loops to optimize electrode-tissue contact.11

**Electrophysiological Indices**

It is noteworthy that neither atrial effective refractory periods nor atrial fibrillation cycle lengths were predictive of procedural success. After right atrial ablations alone, right atrial but not left atrial fibrillation cycle lengths were prolonged. After left atrial ablations were added to right atrial ablations, both the right and left atrial fibrillation cycle lengths increased. Possible explanations for these observations are that (1) the left atrium is the dominant atrium during atrial fibrillation, and to have an impact on the level or organization of the atrial fibrillation, left atrial lesions are necessary, or (2) a critical number of lesions throughout both atria are necessary to result in a significant impact on the level of organization of the atrial fibrillation. Because lesions were placed sequentially in the right atrium followed by the left atrium in all animals, this issue cannot be resolved with these data.

The relatively large interelectrode spacing of the basket electrode resulted in insufficient resolution to map individual atrial fibrillation wavelets, but atrial tachycardias could be mapped. When an electrode on the basket catheter demonstrated middiastolic potentials, a standard ablation catheter could be positioned at that site to ablate the region of slowed conduction.

**Atrial Tachycardias**

Regular atrial tachycardias that had characteristics of reentrant rhythms with excitable gaps were observed during and after atrial ablations. Possible explanations for the occurrence of these tachycardias are that (1) they occur as a proarrhythmic complication of the ablative lesions, (2) they result from an incomplete therapeutic result of the procedure (atrial tachycardia being an intermediate stage between atrial fibrillation and sinus rhythm), or (3) they are a primary manifestation of the atrial myopathy that results from chronic rapid atrial pacing and mitral regurgitation. Although this investigation was not designed to resolve that issue, it has been observed that linear atrial ablations in normal canine atria can result in sustained atrial tachycardias, suggesting that atrial tachycardia can be a complication of ablation.12 Because progressive atrial ablation prolongs the atrial fibrillation cycle length, it seems likely that atrial tachycardia can occur along the therapeutic progression from atrial fibrillation to sinus rhythm. Finally, because atrial tachycardia occurred in the control animals, one can conclude that these tachycardias can be a manifestation of the atrial myopathy that results from rapid atrial pacing combined with mitral regurgitation.

**Study Limitations**

The present investigation was conducted in a canine model, which limits generalization of the conclusions to human atrial fibrillation. The ability to induce atrial fibrillation with programmed atrial stimulation is a surrogate end point for spontaneous arrhythmia recurrence. Although it is possible that the general anesthetic agents used may have altered the hemodynamic and electrophysiological properties of the atrial myocardium, this seems unlikely, given the significant differences between atrial fibrillation inducibility in the ablation and control groups. It is proposed that specific linear lesions at specific atrial locations resulted in termination and failure of reinduction of atrial fibrillation. An alternative explanation for these observations may be that enough nonspecific injury to the atria was achieved that atrial fibrillation could no longer propagate. Because the duration of sustained atrial fibrillation was limited in the present study, generalization of the results to longer-duration atrial fibrillation should be made with caution. Finally, because high-resolution techniques such as intravascular or transesophageal echocardiography were not available, atrial mechanical function was not assessed.

**Conclusions**

Susceptibility to sustained atrial fibrillation can be reduced by long linear atrial ablations created with specially designed coil electrode catheters. Procedures were successful despite the high prevalence of discontinuous lesions and incomplete lesion sets. Although atrial tachycardias occurred at follow-up, a follow-up tachycardia was successfully mapped and ablated. The procedure was associated with significant mortality (coronary artery embolism, respiratory complications from prolonged anesthesia) and morbidity (complete heart block, sinus node dysfunction). Although this study suggests that the complete set of empirically derived lesions is not
required to terminate atrial fibrillation, further animal studies will help determine which lesions are most efficacious.

Acknowledgment
This study was supported in part by a Grant-in-Aid from the American Heart Association, Virginia Affiliate.

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Linear Atrial Ablations in a Canine Model of Chronic Atrial Fibrillation: Morphological and Electrophysiological Observations
Mark A. Mitchell, Ian D. McRury and David E. Haines

Circulation. 1998;97:1176-1185
doi: 10.1161/01.CIR.97.12.1176

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1998 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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