Catheter Ablation of Ventricular Epicardial Tissue
A Comparison of Standard and Cooled-Tip Radiofrequency Energy

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Background—Transthoracic epicardial catheter ablation is an emerging catheter ablation strategy being used clinically at increasing frequency. However, the efficacy of standard RF ablation on the epicardial surface of the heart is hindered by (1) the lack of convective cooling of the ablation electrode and (2) the varying presence of epicardial adipose tissue interposed between the ablation electrode and the target site. This experimental animal study examines the biophysical characteristics of radiofrequency (RF) ablation lesions generated by either standard or cooled-tip ablation of the ventricular epicardium.

Methods and Results—Nonsurgical subxyphoid pericardial access was achieved in 10 normal goats and 7 pigs with healed myocardial infarctions. A 4-mm cooled-tip RF ablation catheter (continuous 0.9% saline circulation at 0.6 mL/s; goal temperature, 40°C; 60 seconds) was used to deliver epicardial ventricular lesions: 47 in normal tissue and 22 in infarcted tissue. Standard RF ablation lesions (n=33) using a 4-mm top catheter (goal temperature, 70°C; 60 seconds) were also placed on normal epicardial tissue. Lesions created with standard and cooled-tip RF ablation were 3.7±1.3 mm (25±16.8 W) and 6.7±1.7 mm (44.8±6.8 W) in depth, respectively. On scar tissue, lesions made with the cooled-tip catheter measured 14.6±2.7 mm in length, 11.8±2.9 mm in width, and 5.6±1.2 mm in depth (35.6±7.1 W). In areas covered by epicardial fat (3.1±1.2 mm thick), standard RF energy did not generate any appreciable lesions, but cooled-tip RF lesions were 4.1±2 mm in depth (45±4.4 W).

Conclusions—Cooled-tip RF ablation can generate epicardial lesions more effectively than standard RF ablation and appears to be of particular benefit in ablating areas with overlying epicardial fat. (Circulation. 2004;109:2363-2369.)

Key Words: catheter ablation • electrophysiology • myocardial infarction • pericardium

The presence of epicardial circuits may adversely affect the outcome of radiofrequency (RF) catheter ablation (RFA) of ventricular tachycardia (VT). The prevalence of intramural or epicardial VT circuits appears to be dependent on the cause of the underlying heart disease, ranging from 15% in post–myocardial infarction patients1,2 to 40% in patients with Chagas’ disease.3 A few reports have also described epicardial VTs in patients with structurally normal hearts.4 It is well established that active cooling of the RFA electrode with infused saline can enhance the depth of endocardial penetration of RF energy and enlarge lesion size.5,6 However, even when a cooled-tip RFA catheter is used, truly epicardial circuits are unlikely to be eliminated with endocardial RF pulses.3,7,8

Epicardial VT circuits can be ablated by use of a percutaneous transthoracic approach and standard RF ablation with an acute success rate between 60% and 75%.2,3 However, the lack of convective cooling of the ablation electrode by the blood would be expected to limit power delivery in the pericardial space. This suggests that standard RFA may not be as effective when delivered to the epicardium compared with lesions delivered to the endocardium. In a previous experimental animal study, standard RF energy applications delivered to the normal epicardium produced lesions 2.67±0.35 mm in depth when RF applications were delivered for 59.4±3 seconds with a mean temperature of 71.3±4.5°C and 3.5±1.75 W.9 Furthermore, the efficacy of epicardial ablation may be attenuated by the presence of epicardial adipose tissue that may be interposed between the ablation electrode and a putative target site.

The use of a cooled-tip ablation electrode might allow for the generation of larger and deeper epicardial lesions compared with standard RF energy pulses. Using experimental caprine and porcine model systems, we studied the dimensions and characteristics of standard and cooled-tip (internal saline irrigation) RFA lesions delivered to normal or infarcted...
epicardial tissue. In addition, the effect of epicardial fat on lesion formation was studied. These results provide an experimental basis for the use of epicardial cooled-tip RFA, which in turn may increase the efficacy of VT ablation.

**Methods**

The experimental protocol was approved by the Massachusetts General Hospital Subcommittee on Research Animal Care. The study was divided into 2 parts. Initially, 10 healthy goats (normal caprine model) weighing 40 to 70 kg were used to evaluate lesion characteristics and RF energy parameters during applications delivered to normal epicardial ventricular tissue. Then, 7 adult swine (porcine infarct model) weighing 30 to 50 kg underwent a myocardial infarction procedure as described below. Four to 6 weeks after the infarction procedure, the animals underwent electrophysiological studies to evaluate lesion characteristics and RF energy parameters during applications delivered to infarcted epicardial tissue. All animals were ventilated mechanically with 60% oxygen/40% N2O; a surgical plane of general anesthesia was maintained with 1.5% to 3% isoflurane throughout the experiments.

**Porcine Chronic Infarct Model**

The infarction procedure was performed by injecting agarose gel beads into the mid left anterior descending coronary artery as previously described. Typically, a bipolar voltage map of the chamber was displayed: which electrogram values recorded at selected points were projected. 3D representations of the cardiac chambers were constructed, onto these reference transducers by triangulating the measured distances. Reference system inside the heart. The position of the target trans- ventricular apex and within the coronary sinus to establish a containment the ultrasound transducers were positioned at the right coronary artery. Thirty seconds after balloon inflation (6 atm), 300 μL/1.5 mL saline of agarose gel beads (75 to 150 μm in diameter, Bio-Rad Laboratories) were injected. The animals were housed in an animal facility for 4 to 6 weeks to allow maturation of the infarct scar.

**Access to the Pericardial Space**

A catheter was placed into the pericardial space by use of the transthoracic subxiphoid puncture approach as previously described. Briefly, a 9F sheath was placed into the left femoral artery to allow arterial access, and a 2- to 2.5-mm angioplasty balloon was advanced to the mid left anterior descending coronary artery. Thirty seconds after balloon inflation (6 atm), 300 μL/1.5 mL saline of agarose gel beads (75 to 150 μm in diameter, Bio-Rad Laboratories) were injected. The animals were housed in an animal facility for 4 to 6 weeks to allow maturation of the infarct before the ablation protocol.

**Electroanatomic Mapping and Localization of the Ablation Lesions**

In this study, a sonomicrometry-based electroanatomic mapping (SEAM) system, the RPM System (Realtime Position Management System; Boston Scientific–EP Technologies, Inc) was used to generate an epicardial cast of the ventricular chambers of the heart. This technology measures distances between ultrasound transducers located on the catheters by measuring the time required for ultrasound pulses to travel between transducers. The reference catheters containing the ultrasound transducers were positioned at the right ventricular apex and within the coronary sinus to establish a reference system inside the heart. The position of the target trans- ventricular apex and within the coronary sinus to establish a containment the ultrasound transducers were positioned at the right coronary artery. Thirty seconds after balloon inflation (6 atm), 300 μL/1.5 mL saline of agarose gel beads (75 to 150 μm in diameter, Bio-Rad Laboratories) were injected. The animals were housed in an animal facility for 4 to 6 weeks to allow maturation of the infarct scar.

**Cooled-Tip RF Ablation Protocol**

Epicardial applications of RF energy were delivered in 7 goats at randomly selected disparate sites. A total of 47 applications were delivered to the normal epicardium with a cooled-tip RFA catheter incorporating the SEAM localization technology (Chilli ablation catheter; Boston Scientific–EP Technologies, Inc). This is a 120-cm, 7F deflectable, quadripolar catheter with an interelectrode distance of 2.5-2 mm and a 4-mm tip distal ablation electrode containing a thermocouple. A closed-circuit internal irrigation cooling system allows saline circulation at 0.6 mL/s. The SEAM system was used to maintain and sustain electrode–tissue contact by ensuring that the electrode was oriented toward the myocardium. RF applications were initiated after saline irrigation decreased the measured electrode temperature to <32°C. The energy output was titrated to achieve a maximal tip temperature between 37°C and 40°C either for 60 seconds or until the impedance exceeded 250 Ω.

Twenty-two cooled-tip ablation lesions were also delivered to the epicardial surface of the scar in the 7 porcine chronic infarction models. Temperature, power, and impedance were monitored and recorded. The applications were delivered either for 60 seconds, until an audible impedance pop, until impedance rise >20 Ω, or until catheter dislodgement.

**Standard (‘‘Temperature-Controlled’’) RF Ablation Protocol**

A total of 33 standard RFA lesions (without active saline cooling) were placed onto the epicardial surface of 3 other normal goats with either the 4-mm cooled-tip RFA catheter incorporating the SEAM localization technology or another 4-mm tip RFA catheter with an incorporated thermocouple (Navistar, Biosense-Webster, Inc). The RF generator used was either the Cardiac Pathways RF generator or the Stockert generator (Biosense-Webster, Inc). Power, impedance, and temperature were continuously monitored. Applications were controlled for a constant temperature of 70°C and delivered for a total of 60 seconds.

**Postablation Processing**

At least 30 minutes after the final ablation lesion, the animals were euthanized and the hearts excised. Lesions on the epicardial surface were measured with a surgical ruler to quantify the length along the long axis, short axis, and depth. Sections from grossly detectable lesions were fixed in 10% formalin; the tissue was dehydrated, embedded in paraffin, sectioned at 5-μm thickness, and stained with hematoxylin and eosin and/or Masson’s trichrome.

**Statistical Analysis**

Pearson correlation analysis was performed. Multiple regression models were constructed to assess the relationship between lesions, dependent variables, and predictor variables across different methods. Statistical analysis was performed with SAS software (SAS Institute, Inc). The values were expressed as mean±SD, and a value of $P<0.05$ was considered to be statistically significant.

**Results**

**Standard RF Ablation**

A total of 80 RF energy applications were delivered to 10 normal animals, of which 33 were standard temperature-controlled applications. Eleven of 33 pulses were delivered to epicardial tissue covered by fat, whereas the remaining 22 pulses were delivered to epicardium without overlying epicardial fat. Three lesions were not found during gross pathological inspection of the heart.

As shown in Table 1, standard RFA lesions were 3.7±1.3 mm in depth in areas without epicardial fat. However, in areas in which epicardial fat was present (on average, this tissue was 3.1±1.2 mm thick), standard RF did not create...
any appreciable lesions in the myocardial tissue. The lesions were not transmural in the 5 applications placed on the right ventricular wall; however, the caprine right ventricular wall is known to be significantly thicker than seen in humans. The mean power output was 23.8 ± 18 W and resulted in an impedance drop of 22.6 ± 3.9 Ω. Impedance rises were seen during 4 applications. These were not followed by an audible pop and were related to spontaneous catheter movement (n = 3) or induction of ventricular fibrillation (n = 1). Tissue cavitation (“cratering”) was not found at gross macroscopy. Pericardial membrane perforation was not seen. A lung lesion was noted in 1 animal, but pleural perforation did not occur. Histological examination revealed homogeneous lesions with smooth borders (Figure 1), as seen during typical endocardial RF lesion deployment.

### Cooled-Tip RF Ablation

The cooled-tip RFA catheter was used to deliver 44 lesions to normal ventricular epicardial tissue, of which 7 and 37 lesions were located at areas with or without overlying fat tissue, respectively (mean thickness of the fat layer was 2.6 ± 1.2 mm). The epicardial electrogram voltage amplitudes at all of the ablation sites were 1.5 mV regardless of the presence of epicardial fat. All cooled-tip RF lesions were identified at necropsy. In the absence of epicardial fat, these cooled-tip RF lesions (6.7 ± 1.7 mm) were significantly deeper than those seen during standard RFA (Table 1). All of the biophysical parameters seen during RF energy delivery, including the magnitude of the impedance drop seen at the end of the application, were similar whether or not the pulse was

#### Table 1. Biophysical Parameters and Lesion Dimensions of Cooled-Tip and Standard RF Ablation Lesions Delivered to Normal and Infarcted Epicardium

<table>
<thead>
<tr>
<th></th>
<th>Cooled-Tip RF Ablation (n=65)</th>
<th>Standard RF Ablation (n=33)</th>
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<tr>
<td></td>
<td>Normal Tissue (n=37)</td>
<td>Normal Tissue on Fat (2.6 ± 1.2 mm, n=7)</td>
</tr>
<tr>
<td>Power, W</td>
<td>44.8 ± 6.8</td>
<td>45 ± 4.4</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>39.7 ± 3.2</td>
<td>40.2 ± 2</td>
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<tr>
<td>Initial impedance, Ω</td>
<td>146 ± 24</td>
<td>146 ± 16</td>
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<tr>
<td>Impedance drop, Ω</td>
<td>27.8 ± 10.3</td>
<td>27.6 ± 10.1</td>
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</table>

**Lesion characteristics**

<table>
<thead>
<tr>
<th></th>
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<th>Standard RF Ablation (n=33)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Normal Tissue (n=37)</td>
<td>Normal Tissue on Fat (2.6 ± 1.2 mm, n=7)</td>
</tr>
<tr>
<td>Long axis, mm</td>
<td>15.9 ± 3.5</td>
<td>15.6 ± 4.2</td>
</tr>
<tr>
<td>Short axis, mm</td>
<td>13.7 ± 3.5*</td>
<td>12.3 ± 4.3</td>
</tr>
<tr>
<td>Depth, mm†</td>
<td>6.7 ± 1.7* (4–9)</td>
<td>4.1 ± 2 (1–7)</td>
</tr>
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*P < 0.05.
†These numbers represent lesion dimensions seen on the myocardial tissue only and do not incorporate the lesion depth in the fat tissue interposed between the catheter tip and the epicardial surface of the heart. Numbers in parentheses indicate range of lesion depth.

**Figure 1.** Cooled-tip and standard RF epicardial ablation lesions. A, Smallest epicardial lesion was generated with standard RF energy (yellow arrow); other 5 lesions were created with cooled-tip RF. B, Contour of a cooled-tip epicardial lesion is seen on normal epicardial surface and on fat (black arrow). Bottom, Histopathological slides of epicardial lesions generated by standard (C) and cooled-tip (D) ablation catheters. Epicardial fat interposed between tip of ablation catheter and epicardium prejudice creation of deep epicardial RF lesions: there is a distinct border to lesion at beginning of epicardial fat layer when standard RF energy is used (C), and significant attenuation of lesion is noted toward area covered by epicardial fat when cooled-tip RF energy is used (D).
delivered on epicardial fat (Table 1). Similarly, the lesion width and length did not vary significantly between these areas. And unlike with standard RFA, these cooled-tip lesions were of significant depth in the presence of epicardial fat (4.07 ± 2 mm). These values were significantly greater than those seen during standard RFA (Table 1). A total of 5 lesions were delivered atop the right ventricular epicardial wall at areas not covered by epicardial fat, and 3 of these were transmural in depth.

Impedance rises were noted during 5 applications. Three of these were preceded by a significant impedance drop (35 ± 5.6 Ω) and coincided with an audible pop. A tissue "crater" was identified at necropsy at each of these sites. The epicardial lesion with the largest impedance drop (41 Ω) was also associated with a contiguous lung lesion (again without pleural perforation). In the 2 other applications, the impedance rise occurred because of catheter movement. Perforation to the endocardium was not seen at these sites. As seen during standard RFA, histological examination of these cooled-tip lesions again revealed homogeneous lesions with smooth borders (Figure 1). There were no instances of pericardial or pleural perforation.

**Porcine Chronic Infarct Model**

With the cooled-tip RFA catheter, a total of 22 epicardial lesions was delivered in 7 chronically infarcted animals. Because of intractable VF after the first application, animal 2 received just 1 RF application. On gross pathological inspection, the RF lesions were located exclusively along and within the borders of the scar (Figure 2). These lesions measured 14.6 ± 2.7 mm in length, 11.8 ± 2.9 mm in width, and 5.6 ± 1.2 mm in depth (Table 1). Lesions placed at the right ventricular aspect of the scar were consistently transmural and ranged from 4 to 5 mm in depth.

The maximal delivered power was 35.6 ± 7.1 W, and the maximal temperature was 41.4 ± 2.2°C. The initial impedance and overall impedance drop during these applications were 110.4 ± 11.9 Ω and 19.7 ± 4.4 Ω, respectively. During 2 of these applications (40 W), an impedance rise associated with an audible pop occurred at 36 seconds in swine 7 and at 53 seconds in swine 1. Crater formation was noted at these sites during the necropsy. Epicardial fat was not present at any of the sites of lesion deployment on the scar.

**Predictors of Lesion Size**

Only nontransmural cooled-tip epicardial pulses delivered at regions without overlying epicardial fat (n=30 pulses) were included in the analysis of the correlation between the biophysical parameters and lesion dimensions. The biophysical parameters analyzed included (1) the maximum temperature achieved, (2) the maximum power achieved, and (3) the impedance drop expressed as a percentage of the initial impedance (impedance % drop). In the univariate analyses, the maximum temperature achieved did not correlate significantly with the any of the lesion dimensions (see Table 2). The maximum power applied correlated only with the depth of the lesion in an inverse manner (R² = −0.14, P = 0.04; r = −0.38, P = 0.04) but not the other lesion dimensions (Table 2). However, there was a statistically significant correlation between the impedance % drop and all of the lesion dimensions: the long axis, short axis, depth, and lesion volume.

Four regression models, 1 multiple and 3 simple, were constructed to investigate the effect of impedance % drop and the maximum power on lesion depth and volume (Figure 3). The model for depth with both of these variables as predictors was highly significant at P < 0.001. Depth was highly affected by impedance % drop (P < 0.003) and maximal power (P < 0.01), with an R² = 0.38. That is, 38% of the variability in lesion depth is explained by the combination of the impedance % drop and maximal achieved power. The equation to predict lesion depth on the basis of these 2 variables is as follows: Lesion depth (mm) = 8.53 + 0.16(x₁) − 0.1(x₂) + 1.99,

<table>
<thead>
<tr>
<th>Lesion Dimensions</th>
<th>% Impedance Drop</th>
<th>Maximum Temperature</th>
<th>Maximum Power</th>
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<tbody>
<tr>
<td>Short axis</td>
<td>0.61 (P &lt; 0.0003)</td>
<td>0.19 (P = 0.32)</td>
<td>0.03 (P = 0.88)</td>
</tr>
<tr>
<td>Long axis</td>
<td>0.56 (P = 0.001)</td>
<td>0.10 (P = 0.59)</td>
<td>0.06 (P = 0.76)</td>
</tr>
<tr>
<td>Depth</td>
<td>0.48 (P &lt; 0.008)</td>
<td>−0.10 (P = 0.60)</td>
<td>−0.38 (P = 0.04)</td>
</tr>
<tr>
<td>Volume†</td>
<td>0.62 (P &lt; 0.0002)</td>
<td>−0.05 (P = 0.79)</td>
<td>−0.03 (P = 0.88)</td>
</tr>
</tbody>
</table>

*Correlation coefficients (r values) and the corresponding P values (in parentheses) are shown in the table.
†The volumes were determined by assuming a hemispheric ellipsoid shape to the epicardial lesions.
where $x_1$ = impedance % drop and $x_2$ = maximal power required. When the only predictor included in the model for lesion depth was the impedance % drop, the $R^2$ drops to 0.23 ($P=0.0007$). The regression models for short axis, long axis, and lesion volume with only impedance % drop and the single predictor were all statistically significant at $P<0.01$ ($R^2=0.38$), $P=0.001$ ($R^2=0.37$), and $P=0.0002$ ($R^2=0.39$), respectively.

**Discussion**

Although epicardial RFA is being used increasingly to treat patients with VT, the optimal means for epicardial lesion formation has not been well studied. The significant findings of this study include the following: (1) cooled-tip RFA allows for greater energy delivery to the epicardium, producing deeper lesions than standard RFA; (2) epicardial fat interposed between the catheter tip and the heart completely abrogates lesion formation with standard RFA; (3) although somewhat attenuated, cooled-tip RFA generates appreciable lesions into ventricular tissue with overlying epicardial fat; (4) the biophysical parameters during RFA do not differentiate between areas with or without epicardial fat; and (5) for infarcted tissue, cooled-tip ablation can efficiently produce deep epicardial lesions.

**Epicardial Temperature-Controlled RF Ablation**

In a previous experimental study, epicardial lesions were generated on normal epicardial tissue with a 4-mm tip temperature-controlled RFA catheter; electrode–tissue contact was ensured by suturing the catheter to the epicardium. The lesions measured $7.75 \pm 2.8$ mm in length, $6.5 \pm 1.6$ mm in width, and $2.67 \pm 0.35$ mm in depth (mean temperature, $71.3 \pm 4.5^\circ$C; power, $3.5 \pm 1.75$ W). These dimensions were similar to but slightly smaller than those observed in the present study with standard RFA. It is likely that because of suboptimal contact during the close-chested procedure in this study, greater passive cooling of the ablation electrode resulted in more energy delivery ($23.8 \pm 18$ versus $3.5 \pm 1.75$ W), thereby producing the deeper lesions ($3.7 \pm 1.3$ versus $2.67 \pm 0.35$ mm). The target temperature was frequently achieved at lower power than typically seen on the endocardium in both studies because of the absence of convective cooling of the ablation electrode by the bloodstream.

**Epicardial Cooled-Tip RF Ablation**

By actively cooling the ablation electrode, it was anticipated that more energy could be delivered into the target tissue, generating more efficient lesions. Furthermore, on the basis of the heating efficiency equation postulated for endocardial ablation, one might expect RFA efficiency with active cooling to be even greater on the epicardial surface. That is, given equivalent catheter–tissue contact, a fixed amount of power delivery could result in greater tissue absorption during epicardial ablation because of the absence of current shunting by the bloodstream.

A few preliminary reports have examined the use of cooled-tip RF ablation in the pericardial space. Fenelon found that cooled-tip RFA allowed delivery of high power outputs (42 W/40°C) and produced epicardial lesions with a depth of $6.5 \pm 2.1$ mm (published in abstract form, American College of Cardiology 2002). Wallick found that with equivalent temperature and power settings, cooled-tip ablation produced statistically nonsignificant deeper epicardial than endocardial lesions ($4.45 \pm 1.5$ versus $3.55 \pm 1.2$ mm; published in abstract form, NASPE-Heart Rhythm Society 2002). But in both studies, RF energy was delivered only to normal epicardial tissue.

In the present study, cooled-tip RFA produced significantly deeper lesions than standard ablation. Indeed, cooled-tip lesions delivered atop epicardial infarcted tissue were deeper than standard RF lesions delivered to normal epicardial tissue and were consistently transmural over the thinner right ventricle. Despite the absence of blood flow, it is significant that the power output during many of the cooled-tip epicar-
dial applications was nearly maximal (50 W). This is probably because of poor electrode–tissue contact. Although the pericardial cavity is a virtual space, if the catheter tip is oriented such that the parietal pericardium is stretched away from heart, the distal electrode may achieve poor contact with the epicardium while manifesting “normal” electrogram characteristics because of myocardial contact with the proximal electrode.\textsuperscript{12} Regarding this point, SEAM was helpful in verifying that the electrode orientation was directed toward the myocardium.

Among the biophysical parameters examined, the magnitude of the impedance drop correlated best with lesion dimension. However, in the regression analysis, the lesion depth was best predicted by a model incorporating a combination of the impedance drop and power ($R^2=0.38$). Specifically, the deepest lesions were observed when a large impedance drop was achieved with less power delivery. These data suggest that 38% of the variability in the lesion depth is explained by the combination of these 2 predictors. Because the electrode temperature was held constant by the saline irrigation, reduced power delivery is suggestive of better electrode–tissue contact. And unlike standard RFA, in which suboptimal electrode–tissue contact may permit passive electrode cooling, during cooled-tip ablation, sustained contact appears most conducive to lesion formation.

**Crater Formation at the Epicardial Surface**

By cooling the ablation electrode during RF delivery, the maximal tissue temperature is displaced further into the myocardium, allowing deeper lesion formation. However, sudden expansion of intramyocardial gas and crater formation can occur when the tissue temperature exceeds 100°C. This typically manifests during endocardial ablation by a sudden “popping” noise with a concomitant rise in the impedance. As with endocardial ablation, crater formation and impedance “popping” were noted during epicardial cooled-tip ablation. Although a greater impedance drop was noted during RF pulses that resulted in craters (35 ± 5.6 versus 27.8 ± 10 Ω), no specific cutoff in the magnitude of the impedance drop could be identified as a threshold limit. Nonetheless, these data suggest that real-time monitoring of the impedance drop may minimize the risk of crater formation; that is, active power titration to achieve a more gradual impedance drop. The maximal tissue temperature during standard RFA is not expected below the electrode–tissue interface; accordingly, impedance “pops” were not noted during standard epicardial ablation.

Unlike endocardial impedance “pops,” which are particularly thrombogenic, epicardial impedance popping and crater formation are of unclear clinical relevance. It is less likely that these phenomena would result in major adverse clinical sequelae. However, one cannot rule out the possibility that the thinner right ventricular wall may be susceptible to acute or subacute cardiac perforation. Although adverse events were not noted in the present study, these were nonsurvival experiments and do not address the possibility of unforeseen chronic sequelae. In any event, it seems prudent to avoid impedance “pops” and crater formation even during epicardial ablation. Novel devices incorporating impedance-guided ablation may prove useful in this regard.

**Effect of Epicardial Fat**

The low electrical and thermal conductivity properties characteristic of fat make it less likely for RF current and heat conduction, respectively, to penetrate to underlying myocardial tissue. Atop fat, the target temperature is reached at lower power, resulting in a shallow lesion. Accordingly, during temperature-controlled RFA, areas covered by epicardial fat required less power and resulted in a smaller impedance decay compared with areas without epicardial fat. Conversely, cooled-tip ablation was more effective than standard RFA in ablating epicardial target tissue covered by overlying fat. Standard RF pulses delivered on epicardial fat did not result in appreciable lesion depth; however, cooled-tip ablation delivered through an epicardial fat layer measuring $2.6 \pm 1.2$ mm generated lesions similar in size to standard RFA lesions in areas without epicardial fat (Table 1). But even cooled-tip ablation was unable to produce epicardial lesions through fat thicker than 3.5 mm. However, only 3 cooled-tip RF pulses were delivered atop a fat layer $>3.5$ mm.

The present study did not specifically address the efficacy of cooled-tip RFA of scarred myocardial tissue with overlying epicardial fat. But because epicardial fat cannot be reliably predicted by electrogram characteristics or differences in the pacing thresholds,\textsuperscript{15} cooled-tip RFA may be the preferred epicardial RF ablation modality.

**Ancillary Damage to Adjacent Structures**

**Lungs**

It has been suggested that pulmonary damage during epicardial catheter ablation results from passive heat conduction from the catheter tip and not from resistive heating of the tissue.\textsuperscript{5} However, lung lesions were not identified during any of the 23 temperature-controlled standard RF applications but only in the single cooled-tip ablation experiment in which the largest impedance drop (41 Ω) was observed. Thus, ancillary lung damage appears most dependent on the contact and orientation of the catheter tip relative to the lung tissue.

**Epicardial Coronary Vessels**

We previously demonstrated that when delivering standard RFA lesions in the vicinity of a coronary artery, susceptibility to chronic vascular damage is inversely proportional to vessel size.\textsuperscript{5} Severe hyperplasia and/or endovascular thrombosis occurred only in vessels with an internal diameter $\leq 0.24 \pm 0.15$ mm. Vessels with an internal diameter of $0.51 \pm 0.3$ mm demonstrated matrix proliferation in the media but no endothelial disruption, neointimal proliferation, or intravascular thrombosis. One possible explanation is that larger vessels are protected by greater blood flow. However, the greater power delivered during cooled-tip RFA might not demonstrate the same safety performance characteristics near epicardial coronary vessels. In the present study, some cooled-tip RF applications were delivered in the vicinity of a coronary artery, and no clear evidence of endothelial disruption or intravascular thrombosis was seen. However, further
investigation is necessary to fully establish its safety near coronary arteries.

**Potential Clinical Implications**

These data raise the possibility that midmyocardial and perhaps even endocardial VT circuits may be eliminated by cooled-tip RFA from the pericardial space. A predominantly epicardial approach to VT ablation is attractive because of (1) the ease of epicardial catheter manipulation and (2) the absence of endovascular complications such as thromboembolism. However, direct evidence of epicardial ablation of endocardial VT circuits is lacking. Moreover, only 3 applications delivered to the right ventricular outflow area resulted in transmural lesions in normal animals. In the infant-model animals, 7 lesions were found to be transmural: 6 related to the right ventricular extension of the anterior myocardial infarction and 1 in the left ventricular portion of the scar. Additional work is needed to establish whether the results obtained during endocardial "substrate mapping" of poorly tolerated VT can be reproduced with the epicardial approach.16–18

A bipolar electrogram amplitude of <1.5 mV was used to define abnormal epicardial tissue,12 but further epicardial mapping studies of patients with normal left ventricles are necessary to fully define normal values.

It may not be appropriate to extrapolate these results to RFA catheters with other active or passive means of electrode cooling. Specifically, saline cooling of the ablation electrode by external irrigation is known to be an effective means of generating deep endocardial RF lesions.14,18 But in the pericardial space, (1) irrigation of the electrode with saline, a conductive solution, may increase the size of the virtual ablation electrode to uncontrollable dimensions because of the absence of the dispersing "buffering" effect of the bloodstream, and (2) the volume of infused fluid into the pericardial sac may alter the biophysical properties of each successive ablation pulse, necessitating manual aspiration of the pericardial space before each lesion. Also, no information is available regarding the use of large-tip (eg, 8-mm tip) catheters for epicardial mapping and ablation. Thus, further work is necessary to understand the use of these RFA technologies in the pericardial space.

**Conclusions**

Cooled-tip RFA produces larger and deeper epicardial lesions than standard RFA. The presence of epicardial fat interposed between the catheter tip and the myocardial tissue prevents lesion formation with standard RFA but only moderately attenuates the efficacy of cooled-tip ablation. Over infarcted epicardial tissue targets, cooled-tip RFA was able to generate lesions of substantial depth.

**Acknowledgments**

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