Epicardial Ablation Performance of a Novel Radiofrequency Device on the Beating Heart in Pigs

Yoshiyuki Watanabe, MD, PhD, Timo Weimar, MD, Toshinobu Kazui, MD, Urvi Lee, PhD, Richard B. Schuessler, PhD, and Ralph J. Damiano, Jr, MD

Division of Cardiothoracic Surgery, Department of Surgery, Washington University School of Medicine, Barnes-Jewish Hospital, St. Louis, Missouri

Purpose. Only bipolar clamps create reliable transmural lesions on the beating heart. This study evaluated the performance of a new radiofrequency (RF) device on the beating heart in an acute porcine model.

Description. Six domestic pigs were ablated with a novel bipolar RF linear device on the beating heart (ablation time of 40 s, 3 each on right and left atria and 1 each on superior and inferior vena cavae). The heart was stained with 2, 3, 5-triphenyl-tetrazolium chloride, and each lesion was cross-sectioned for lesion depth and transmurality.

Evaluation. Transmurality was documented in 89% of the cross-sections. Sixty-three percent of lesions were transmural along the entire lesion length. Overall, 85% of the nontransmural cross-sections were located on the right atrium, and half of the non-transmural sections were in the superior or inferior vena cavae lesions.

Conclusions. This novel device was able to create transmural lesions on the beating heart, more effectively in the left atrium than in the right atrium.

The introduction of new surgical ablation technologies has simplified the surgical treatment for atrial fibrillation (AF) [1]. The original “cut-and-sew” Cox-maze procedure has been replaced by alternative energy sources [2]. In particular, bipolar RF clamping devices have been shown to reliably create transmural lesions, and these ablation lines have been used to replace most of the incisions of the Cox-maze III procedure [3]. This iteration of the procedure has been termed the Cox-maze IV (CMIV) [4].

In studies from our laboratory, epicardial transmural lesions have been created with a bipolar RF pen device, the Isolator Transpolar Pen and the Atricure Coolrail (AtriCure Inc, West Chester, OH), on the beating heart in atrial tissue [5, 6]. The transpolar pen could reliably create transmural lesions in tissue up to 6 mm thick [5]. However, to create a linear lesion would require multiple overlapping lesions, with an increased risk of loss of continuity. To overcome this shortcoming, the Coolrail linear bipolar probe was developed. Unlike the pen, this device was not able to create lesions that were uniformly transmural along its entire length [7]. To improve upon this performance, a novel RF device with a shorter electrode length and flexible head was designed for epicardial ablation device (Isolator® Linear Pen, AtriCure Inc., West Chester, OH).

In the present study, we tested the hypothesis that this device could epicardially create transmural atrial lesions on the beating animal heart in an acute swine model, that has been well established in our laboratory to study epicardial ablation [5–7].

Technology

Six domestic pigs weighing 70 to 90 kg were used in this study. All animals received humane care in compliance with the “Guide for the Care and Use of Laboratory Animals” (National Academy Press, Washington, DC). A median sternotomy and pericardiotomy were performed to expose the heart [6]. The Atricure Isolator Linear Pen (Atricure, Cincinnati, OH) was used for all ablations in this study (Fig 1). The head of the probe can change angles vertically to provide good epicardial surface contact during ablation. Two electrodes are embedded on the probe head with a 3.35 mm interelectrode spacing. The
electrode lengths were 2 cm and the probe head width was 9 mm.

**Technique**

Eight experimental linear lesions were created epicardially with this device in each animal. Three lesions were created on both the right atrium (RA) and left atrium (LA) free walls. Because of a small LA in 1 animal, only one LA lesion was created. An ablation line also was made on the RA free wall toward each vena cava (Fig 2). That was done to recreate the cava-to-cava ablation line of the CMIV procedure. Ablations were performed for 40 s. Between ablations, the device was cooled with topical application of cold saline. The electrodes were cleaned between each ablation to remove any char.

After completion of the lesion set, the lesion cross-section was made, as described in numerous previous studies from our laboratory [3, 5, 6]. These cross-sections were digitally photographed next to a caliper for calibration. Lesion depth and tissue thickness were determined with commercial software (Adobe Photoshop, San Jose, CA) [5, 6]. The lesion depth was measured from the unstained area to the pink halo region surrounding each lesion.

Values are expressed as mean ± SD. The χ² test and Fisher’s least significant difference test were used for comparisons between independent groups, and Student’s t test was used for two-group comparisons. All statistical analysis was performed with commercial software (IBM SPSS Statistics version 19; SPSS, Chicago, IL).

**Clinical Experience**

A total of 46 lesions and 234 histologic cross-sections were examined. There was no epicardial char or clot on the endocardial surface for any ablation. No animal died in this study.

Cross-sectioned samples of transmural or non-transmural tissue are shown in Figure 3. The efficacy of this novel device is best depicted by a graph showing lesion depth against wall thickness for each ablation (Fig 4). We have used this in previous studies of other ablation technology [2]. Perforations, which caused bleeding requiring a suture to control, occurred in 5 (11%) of the ablations and only occurred during RA ablation. Perforations were always associated with tissue-popping. Impedance between the two electrodes of the probe was recorded as a potential real-time measurement of transmurality during the ablation [8]. Twenty-six percent of the ablations had an impedance drop but there was no significant correlation with popping (p = 0.95), perforation (p = 0.34), or transmurality (p = 0.96; Table 1).

Transmurality was documented in 89% (208 of 234) of the tissue cross-sections and 63% (29 of 46) of all lesions were transmural along their entire lesion length. Transmurality of end cross-sections was 86% (79 of 92), and transmurality of middle cross-sections was 90% (129 of
The transmurality of cross-sections when the wall thickness was 2 mm or greater was 89%, and was not different when the wall thickness was less than 2 mm (85%, \( p = 0.88; \) Table 2).

The transmurality of the LA cross-sections was 95%, which was significantly greater than the RA, superior vena cava (SVC), and inferior vena cava (IVC) cross-sections (RA plus SVC/IVC, 85%, \( p < 0.01; \) Fig 5A). The transmurality of the entire linear ablation lesion was greater in the LA (81%) compared with the RA (53%, \( p < 0.01; \) Fig 5B).

Of all the nontransmural cross-sections (total 26 sections), 50% (13 of 26) were located on a lesion end. A majority of nontransmural sections were located in RA and SVC/IVC (85%). Half of the nontransmural sections were on the SVC and IVC. Seventy-seven percent (20 of 26) of all nontransmural sections occurred when wall tissue was less than 2 mm thick (Fig 6).

Fig 3. Cross-sectioned samples of (A) nontransmural tissue and (B) transmural tissue after triphenyltetrazolium chloride staining. The epicardial surface is on the right side of the tissue samples. The nontransmural tissue is indicated by red color.

Fig 4. Performance of the Isolator Linear Pen device, showing the wall thickness plotted against the lesion depth for all the cross-sections analyzed: (A) transmurality (all locations); (B) transmurality, left atrium; and (C) transmurality, right atrium. Data points falling on the line are completely transmural.
This study demonstrated the performance of a novel bi-polar RF device that has been recently introduced into clinical practice. Previous studies of different ablation technologies demonstrated that most devices can reliably create transmural lesions on cardiopulmonary bypass, but had difficulty on the beating heart [9]. The exception has been bipolar clamp RF devices, which have reliably created transmural lesions on the beating heart in animal models [3, 4, 8]. Although the bipolar RF clamping device can be used to isolate the pulmonary veins, they are incapable of replicating the other ablations of the CM procedure on the beating heart unless one jaw is placed inside the atria. The risk of bleeding and creating an air embolism makes this approach not clinically viable. This is a problem as our group and others have shown that a more extended lesion set is necessary to achieve high success rates, particularly in patients with persistent, longstanding atrial fibrillation [10, 11]. Thus, there is a need to develop an epicardial device that can reliably create linear lesions on the beating heart.

The device was most effective in the LA. When looking at all the LA cross-sections, 95% were transmural, and 81% of the LA lesion lines created by the device were transmural with a single application. This result was significantly better than in our previous studies with other linear epicardial devices. However, the transmurality of the right-sided lesions (RA, SVC, and IVC lesions) was significantly lower, with a majority of the non-transmural lesions located near the SVC and IVC. It was surprising that SVC/IVC lesions had a significantly lower success rate of transmurality than LA lesions, even in very thin tissue (<2 mm). That may be the result of the cooling effect of circulating blood, which limits lesion penetration to the endocardial surface in regions of high blood flow like the SVC/IVC. The microwave ablation device does not create transmural atrial lesions in the beating heart, but did create transmural lesions when endocavitary blood loss was reduced either with cardiopulmonary bypass or by arresting the heart [12]. When utilizing a bipolar clamp device, changes in tissue conductance have been an excellent indicator of

<table>
<thead>
<tr>
<th>Table 1. Ablation Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total lesions, n</td>
<td>46</td>
</tr>
<tr>
<td>Total histologic cross-sections, n</td>
<td>234</td>
</tr>
<tr>
<td>Tissue thickness, mm, mean ± SD (range)</td>
<td>1.47 ± 0.87 (0.32–4.83)</td>
</tr>
<tr>
<td>Thick tissue ≥ 2 mm</td>
<td>80% (87/234)</td>
</tr>
<tr>
<td>Thin tissue &lt; 2 mm</td>
<td>20% (47/234)</td>
</tr>
<tr>
<td>Edge section</td>
<td>40% (92/234)</td>
</tr>
<tr>
<td>Middle section</td>
<td>60% (142/234)</td>
</tr>
<tr>
<td>Popping</td>
<td>57% (26/46)</td>
</tr>
<tr>
<td>Perforation</td>
<td>11% (5/46)</td>
</tr>
<tr>
<td>Impedance drop</td>
<td>26% (12/46)</td>
</tr>
</tbody>
</table>

Total lesions are the number for the entire ablation lesion.

<table>
<thead>
<tr>
<th>Table 2. Transmurality Detail</th>
<th>Transmurality</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histologic cross-section</td>
<td>89% (208/234)</td>
<td></td>
</tr>
<tr>
<td>Lesion</td>
<td>63% (29/46)</td>
<td></td>
</tr>
<tr>
<td>Edge lesion</td>
<td>86% (79/92)</td>
<td></td>
</tr>
<tr>
<td>Middle lesion</td>
<td>90% (129/142)</td>
<td>0.24</td>
</tr>
<tr>
<td>Thick tissue ≥ 2 mm</td>
<td>89% (167/187)</td>
<td></td>
</tr>
<tr>
<td>Thin tissue &lt; 2 mm</td>
<td>85% (40/47)</td>
<td>0.88</td>
</tr>
<tr>
<td>Popping</td>
<td>65% (17/26)</td>
<td></td>
</tr>
<tr>
<td>Nonpopping</td>
<td>60% (12/20)</td>
<td>0.96</td>
</tr>
<tr>
<td>Perforation</td>
<td>40% (2/5)</td>
<td></td>
</tr>
<tr>
<td>Nonperforation</td>
<td>66% (27/41)</td>
<td>0.34</td>
</tr>
<tr>
<td>Impedance drop</td>
<td>58% (7/12)</td>
<td></td>
</tr>
<tr>
<td>Nonimpedance drop</td>
<td>65% (22/34)</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Fig 5. Transmurality of each location by (A) cross-sections and by (B) entire lesion length. The number of the cross-section or entire lesion that were transmural and the total number of cross-sections or lesions examined for each dose are shown. *Denotes p < 0.01. (LA = left atrium; RA+SVC/IVC = right atrium [RA] lesion including both superior vena cava [SVC] and inferior vena cava [IVC] lesions.)

![Graph A](image1.png)

![Graph B](image2.png)
transmurality [8]. However, when using this epicardial device, impedance drop did not correlate with transmurality. The reasons for that may be due to the more focused delivery of energy, the more uniform tissue contact, the exclusion of endocavitary blood flow, and the bidirectional nature of current delivery when using a clamp as opposed to an epicardial linear device.

Tissue perforation occurred in 11% of lesions. Allowing the probe to cool, or actively cooling it with saline, prevented the perforations from occurring. Because this could be a significant clinical problem, it is important to allow the device to cool between each application. The Isolator Linear Pen has no irrigation system, and the probe heats up with repeated use. Our previous studies of the Coolrail device showed that epicardial ablation caused no tissue disruption and no char across the entire tissue in an acute animal model [6, 7]. Therefore, after the initial problem of perforations in the present study, the Isolator Linear Pen was cooled with topical application of cold saline and the electrodes were cleaned to prevent char and excessive heat formation.

Study Limitations
The present study used healthy normal porcine atria. It is possible that results would be different in the clinical setting because human atria often have greater wall thickness and more fibrosis and epicardial fat, which could interfere with energy delivery.

Disclosures and Freedom of Investigation

This study was supported in part by National Institutes of Health grants 5R01 HL032257, R01 HL085113, and T32 HL07776. Drs Schuessler and Damiano receive research grants and equipment from AtriCure, Inc. Dr Damiano receives consultant fees from AtriCure and Medtronic.

References


Disclaimer
The Society of Thoracic Surgeons, the Southern Thoracic Surgical Association, and The Annals of Thoracic Surgery neither endorse nor discourage use of the new technology described in this article.

INVITED COMMENTARY
This very insightful work from the St. Louis group [1] deals with one of the most stimulating issues in modern ablation surgery: how to perform a complete Cox maze epicardially, on the beating heart.

The missing piece is how to perform connecting lines in unclampable areas, like between the left and the right pulmonary veins, between the venae cavae and toward the mitral and the tricuspid annulus. Microwave, unipolar radiofrequency, and ultrasound have been tried for this goal, but failed. The Isolator Transpolar (AtriCure, Inc) is the third iteration of an epicardial linear device based on linear ablation with nonclamping bipolar radiofrequency. The first transpolar dry pen was apparently highly effective, but not very suitable for the creation of long continuous lines. The Coolrail (Atricure, Inc), the 3-cm long cooled transpolar radiofrequency device, was more ductile but way less effective on the atrial tissue. This dry linear device seems to catch up consistently on the effectiveness side but at the price of a quite concerning 10% of perforation due to steam popping while performing an ablation line on the beating swine heart. Popping is a consequence of tissue overheating and is particularly worrisome when considering that, in the modern era of epicardial atrial fibrillation surgery, all these devices are meant to be used through ports, in a close chest condition.

Another very concerning aspect of these devices is that overheating of the handpiece might predispose to collateral damage. So all sorts of complications that were basically extinguished after the advent of clamping bipolar radiofrequency, thanks to the virtual absence of thermal spread intrinsic to clamping devices, might actually return to be actual with nonclamping tools. This requires surgical skill, experience, and consideration on behalf of the surgeon delivering the treatment.

On the other side, like its predecessors, transpolar radiofrequency falls short of creating impeccable epicardial linear connecting lines when deployed epicardially on the beating heart. Only 80% of the tested, quite short, ablation lines resulted actually continuously transmural in the reported experimental setting.

Stefano Benussi, MD, PhD
Cardiac Surgery Division
S. Raffaele University Hospital
Via Olgettina 60
20132 Milan, Italy 20132
e-mail: stefano.benussi@hsr.it

Reference