The Heart Surgery Forum #2001-7014
5 (2):100–104, 2002
Online address: www.hsforum.com/vol5/issue2/2001-7014.html

Epicardial Ablation on the Beating Heart: Progress Towards an Off-Pump Maze Procedure

(#2001-7014 … June 27, 2001)

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ABSTRACT

Background: The treatment of atrial fibrillation with unipolar radiofrequency (RF) catheter ablation techniques has been fraught with difficulty. This study was designed to evaluate the potential advantages of bipolar RF energy and its ability to create transmural linear lesions on the beating heart.

Methods: A right thoracotomy was performed on eight adult sheep. A bipolar RF device was inserted and targeted tissue was clamped between the instrument arms. Ablation was performed on the beating heart. Energy was delivered until the tissue conductance between the two electrodes became constant.

Results: A total of 30 lesions were performed. Average ablation time for all lesions was 9.2±3.9 seconds with a mean peak temperature of 48.7±5.8 ^{O}C. Pacing studies demonstrated 100%(30/30) isolation and staining showed that all lesions were transmural.

Conclusions: Epicardially delivered bipolar RF energy was able to reproducibly isolate atrial myocardium. As opposed to other energy sources, lesions were always transmural and can be created within seconds. On-line measurement of conductance correlates with lesion transmurality. This technology has the potential to perform a beating heart MAZE procedure.

INTRODUCTION

Atrial fibrillation (AF) is the most common dysrrhythmia in the United States, with an incidence of 1-2% in the general population [Cameron 1988]. In certain subgroups, such as the elderly, the incidence can be as high as 6% [Reeder 1986]. Although great strides have been made in the treatment of AF, there still exists a significant mortality and morbidity from this disease. Patients with AF are at an increased risk for stroke and other thromboembolic disease. They also suffer from increased morbidity as a result of atrioventricular (A-V) dysynchrony and compromised hemodynamics. It is estimated that AF accounts for 1.4 million outpatient visits and 227,000 hospitalizations each year in the United States alone [National Center for Health Statistics 1997]. Both clinical as well as experimental studies have increased our understanding of the pathophysiology of AF and have enhanced our ability to treat this arrhythmia. The current medical regimen consists of anticoagulation, as well as pharmacological strategies, designed both to control heart rate and to convert the patient to normal sinus rhythm. This regimen, although effective in treating the symptoms of the disease, is by no means a cure. The patient is left with the significant morbidity of anticoagulation and the side effects of the anti-arrhythmic drugs. Moreover, rate control alone does not address the impaired hemodynamics or thromboembolic risk.

The development of the MAZE procedure offers a cure for AF [Smith 1985]. The surgical approach has achieved success rates over 90% and it has been established as the gold standard against which other interventions are judged. The MAZE procedure is based on the theory that AF is the result of macro-reentrant circuits [Cox 1991]. By abolishing these circuits with lines of conduction block created by carefully placed surgical incisions, AF can be eliminated. Despite the clinical success of the MAZE procedure, it has not gained widespread acceptance because of its invasiveness and the length of time required to perform the complicated set of lesions. Recently, interest has turned toward the development of a less invasive procedure. Ideally, this procedure would require less time, could be performed through a small incision or endoscopically, and not require a prolonged period of cardiopulmonary bypass and cardioplegic arrest.

Over the past ten years, there have been significant advances in the development of radiofrequency energy (RF) as a means to ablate myocardial tissue [Kannel 1998, Chen 1999, Tracy 2000, Wood 2000]. This energy delivered in an epicardial or endocardial manner is capable of producing myocardial necrosis and has the ability to electrically isolate myocardial tissue. RF energy has been utilized by electrophysiologists in the ablation of accessory pathways and A-V node re-entry with significant success [Jazayeri 1992]. There also has been much interest in RF ablation for the treatment of AF. However, difficulty remains in using catheter-based techniques to

Presented at the Fourth Annual Scientific Meeting of the International Society for Minimally Invasive Cardiac Surgery, June 27-30, 2001, Munich, Germany.

Awarded runner-up best presentation.

Reprinted from The Heart Surgery Forum, Volume 5, Supplement 3, 2002.

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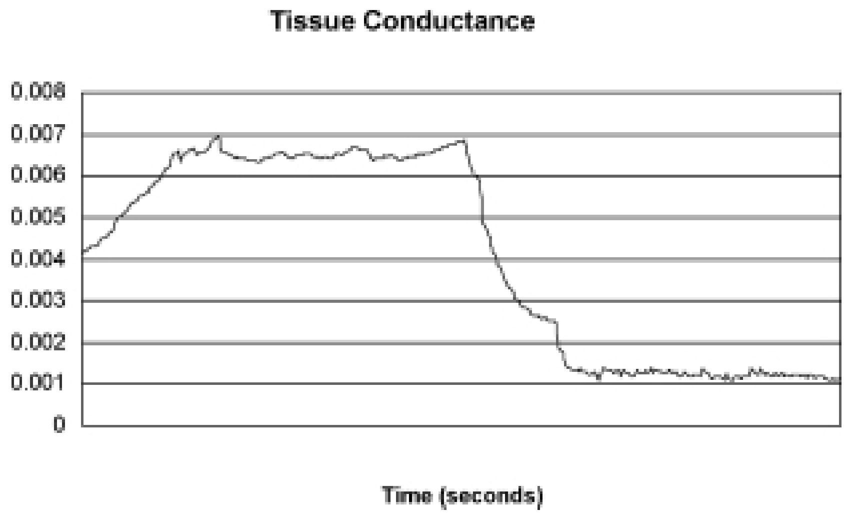

Figure 1. Graphical readout of on-line tissue conductance measurement. This is a logarithmic scale graph of the changes in tissue conductance observed over time in the right atrial myocardium during RF ablation. The Y-axis is in Mho (1/ohms).

create reproducible transmural lesions. These procedures have required lengthy fluoroscopic exposure times and have been plagued both by high complications and low success rates [Jais 1999, Dagres 2001]. The lack of success of catheter-based techniques has led to a resurgence of interest in surgical procedures to treat AF. Our goal was to investigate whether RF energy delivered by a bipolar device could reproducibly create lesions in a rapid and controlled manner that was capable of electrically isolating myocardial tissue.

MATERIALS AND METHODS

Eight adult sheep weighing 50 to 75 kilograms were used in the study. The animals were initially anesthetized with intramuscular ketamine (30mg/kg), followed by inhaled 3% isoflurane. Arterial and venous access was achieved via a cutdown of the carotid artery and external jugular vein, respectively. The arterial pressure and ECG were monitored continuously. A 7 cm. right anterolateral thoracotomy was made in the fourth intercostal space. The pericardium was opened and the right atrium and both vena cavae were exposed. The inferior and superior vena cavae were circumferentially dissected and isolated with umbilical tapes. Care was taken to avoid injury to the phrenic nerve. The right superior and inferior pulmonary veins were also isolated with umbilical tapes.

The heart was paced from the right atrial body and appendage and pacing thresholds were recorded. Pacing was also performed from the right-sided pulmonary veins and from both vena cavae at a distance of one centimeter from the atriocaval junction. The animal was given intravenous heparin (200 units/kg) and an activated clotting time of greater than 200 seconds was maintained throughout the study.

A bipolar RF ablation device was used to create the lesions (Atricure, Inc, Cincinnati, OH). The RF generator was able to control both voltage and current delivery to the electrodes. A specially designed portable computer was used to monitor and record temperature, time, current, voltage, impedance, conductance and energy. The computer system displayed real time continuous graphical data in an easy-to-read and simple format.

Atrial lesions were created by clamping target tissue between the two electrode arms of the device. A cuff of atrial myocardium was ablated around the right atrial appendage, superior vena cava, inferior vena cava, and right-sided pulmonary veins. Radiofrequency energy was delivered at 75 volts and 750 milliamps. The ablation was continued until the tissue conductance between the two electrodes decreased, and achieved a steady state for two seconds [Figure 1,]. Tissue conductance was chosen as an indicator of a complete transmural ablation. Electrical isolation was defined as the inability to capture the body of the right atrium by pacing inside the isolated segment using a stimulus strength of 20 mA.

After documentation of electrical isolation, the animal was sacrificed using sodium pentobarbital and the heart excised en block. The atrium was examined for any evidence of thrombus or stricture. The radiofrequency lesions were grossly examined and tissue stained with one-percent Triphenyltetrazolium chloride (TTC) to document transmurality.

All animals received humane care in compliance with the "Guide for the Care and Use of Laboratory Animals" published by the National Institutes of Health (NIH publication 85-23, revised 1985).

RESULTS

Radiofrequency lesion delivery

A total of 30 circumferential lesions were performed on the cuffs of atrial myocardium surrounding the superior vena cava (SVC), inferior vena cava (IVC), right pulmonary veins (RPV) and the right atrial appendage (RAA) [Table 1,]. Three of the animals did not receive the complete lesion set because of technical difficulty in dissecting the vessels. In the

Table 1. A summary of circumferential ablations done on the beating heart.

Lesion Site	Number	Time (seconds)	Temp (Celsius)	Isolated
Right Atrial Appendage	10	9.3±3.3	47.8±6.4	100%
Superior Vena Cava	6	11.9±5.9	51.2±7.8	100%
Inferior Vena Cava	7	6.7±1.4	47.0±3.8	100%
Right Pulmonary Veins	7	9.2±3.3	49.5±4.8	100%

last two animals, a second RAA lesion was done to connect the initial RAA lesion and produce an isolated section of myocardium. In both animals, the lesion lines overlapped smoothly and the enclosed myocardium was isolated.

The mean ablation time was 9.2 ± 3.9 (range 4.0 - 23.2) seconds with a mean peak temperature of 48.7 ± 5.8 ^{O}C. For lesions (n = 10) done on the RAA, the mean ablation time was 9.3 ± 3.3 (range 6 – 14.8) seconds and mean peak temperature was 47.8 ± 6.4 ^{O}C. The wall thickness of our RAA ranged from 2 to 2.5 mm. The average energy delivered was 166.0 ± 57.0 joules.

For lesions (n = 6) done on the SVC, the mean ablation time was 11.9 ± 5.9 (range 7 – 23.2) seconds with a mean peak temperature of 51.25 ± 7.8 ^{O}C. The wall thickness of the SVC ranged from 0.5 to 0.8 mm. The average energy delivered was 253.0 ± 232.6 joules.

For lesions (n = 7) done on the IVC, the mean ablation time was 6.7 ± 1.4 (range 4 – 8.2) seconds with a mean peak temperature of 47.0 ± 3.8 ^{O}C. The wall thickness of the IVC ranged from 0.4 to 0.8 mm. The average energy delivered was 95.4 ± 17.5 joules.

For lesions (n = 7) done on the RPV, the mean ablation time was 9.2 ± 3.3 (range 6 – 15.8) seconds with a mean peak temperature of 49.5 ± 4.8 ^{O}C. The wall thickness on the RPV varied depending on the fat pad surrounding the RPV-RA junction; the range was from 1.1 to 5 mm. The average energy delivered was 123.0 ± 55.8 joules.

Pacing Results

Before ablation, all potential target tissue sites (30/30) were able to pace the heart 1cm distal to their junction with the atrial myocardium. Pacing thresholds were less than or equal to 1.5 mA along the targeted atrial myocardium. After ablation, pacing from all sites was unable to capture the body of the right atrium at stimulus strengths up to 20 mA. Thus, electrical isolation was documented for all 30 ablation lesions.

Histology

Examination of the atria, vena cava and pulmonary veins revealed no evidence of thrombus or stricture formation. All lesions were examined post-mortem by TTC staining. All lesions were transmural, continuous and linear [Figures 2-3,]. The lesion width was discrete and was variable depending on the depth and time of the lesion. In areas of thin walls (i.e., IVC, SVC), the lesion width was fairly constant at 1mm. On thicker areas of the atrium (i.e., the appendage) where the wall thickness was up to 5mm, the lesion width was never more than 2mm.

DISCUSSION

AF is a common arrhythmia and a major source of morbidity, particularly in the elderly population [Wolf 1979]. Despite advances in endocardial catheter-based techniques, there is still no effective cure for AF except the MAZE procedure. The MAZE procedure works because the surgeon is able to create transmural lesions in the myocardium with a scalpel. This creates lines of conduction block, which termi-

Figure 2A. A photograph of the epicardium of the right atrium after staining with 1% TTC. The lesion line travels circumferentially around the tip of the right atrial appendage. The margins of the ablation line are clear and discrete showing minimal thermal injury to surrounding myocardium. The lesion itself is completely transmural and continuous. The width of this lesion varies from 1.5mm to 2mm.

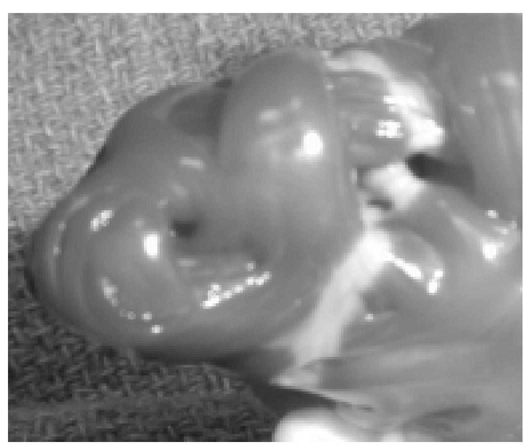

Figure 2B. The endocardial view of the same right atrial appendage lesion. This ablation line is well delineated and varies in width from 1.5mm to 2.0mm as it passes through trabeculae of the appendage.

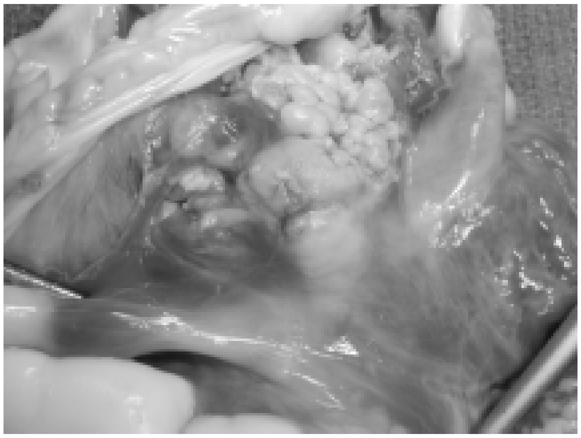

Figure 3A. A photograph of a right pulmonary vein lesion stained with 1% TTC. The lesion was made on the epicardial fat pad covering the pulmonary vein left atrial junction. The lesion travels circumferentially around both pulmonary veins. There was little thermal injury to the surrounding structures.

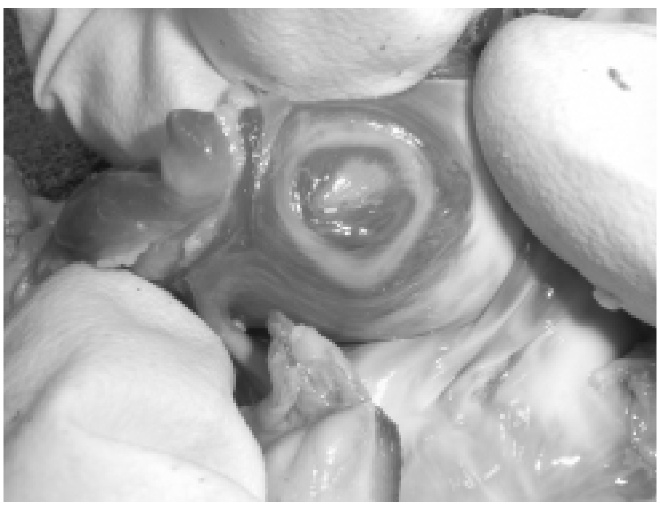

Figure 3B. Endocardial photograph of the same right pulmonary vein lesion. The lesion line can be easily seen circumferentially around each pulmonary vein. The width of this lesion was 0.8 mm to 1.1mm. The lesion was created on atrial myocardium and not on the pulmonary veins, as there is a small rim of atrial tissue distal to the ablation line. Pacing and histology confirmed isolation and transmurality.

nate the reentrant circuits that cause AF. Unfortunately, alternative epicardial and endocardial approaches have failed to produce transmural lesions in a consistent fashion. This is the likely reason underlying the lower success rates seen following catheter-based procedures [Xie 1997].

Unipolar RF catheters require ablation times measured in minutes and often take multiple applications to produce a transmural lesion [Rosenthal 1998]. Unipolar catheters produce electrode temperatures between 80 –90 ^{O}C and can cause severe thermal injury to adjacent tissue. Epicardial RF ablation also is incapable of making a transmural lesion on the beating heart because of the intracavitary heat sink caused by the circulating blood volume. As important, with currently available unipolar RF endocardial and epicardial catheters, there is no way to determine the depth or transmurality of the lesion. RF energy delivery physics is based on the theory that the energy source and the tissue must be in intimate contact [Jais 1999, Dagres 2001]. Uneven pressure or a momentary lapse of contact increases the energy required and results in non-uniformity of the lesion. Unfortunately, current unipolar devices also are not able to assure that a constant pressure is maintained between the electrode and myocardial surface. Thus, there is a pressing clinical need for a device that can reproduce and reliably perform full-thickness endocardial and epicardial ablations.

The device used in this study was able to meet these critical needs. The bipolar RF catheter was able to consistently produce transmural linear lesions. With this device, temperature, current, impedance, conductance, voltage, energy and time were continuously displayed in real time. This provided the surgeon with instantaneous feedback as to the progress of the lesion during the ablation. Changes in tissue conductance gave a 100% correlation with lesion transmurality. As the lesion progressed through the myocardium, the tissue conductance fell progressively. Once the lesion became transmural, the tissue conductance stopped decreasing and reached a steady state. This is the only available device with a measurable end-point indicating transmurality.

Moreover, the time required to produce a transmural linear lesion up to 5 cm long was always less than 30 seconds. By shortening the time required to produce a transmural lesion, patients are exposed to less energy and procedure time. Minimizing the ablation time also maintains the surface temperature of the electrode at more physiological levels. Peak temperature with our device was significantly lower than the 80 to 90 ^{O}C achieved with unipolar RF catheters. Thus, the lesions were more discrete with less damage of the surrounding tissue by histology. This has distinct hypothetical advantages. By protecting the atrial myocardium from unnecessary energy and preventing excessive necrosis and scaring, there should be a better preservation of atrial transport function – a critical outcome variable following the MAZE procedure. Moreover, with more discrete lesions, the risk of both intraoperative and post-operative thromboembolic complications should be greatly reduced. In support of these hypotheses, no intracavitary thrombi were found in this acute study, and there was no evidence of stricture of the pulmonary veins. This is a contradistinction to unipolar energy, which has a high incidence of stricture and thrombosis when applied in or near the pulmonary veins [Taylor 2000].

Using bipolar RF energy, this study has demonstrated for the first time an efficacious method to create transmural atrial lesions from the epicardium on the beating heart. This device has the potential to treat AF in a definitive, safe and expeditious manner. A beating heart MAZE procedure would eliminate the morbidity and mortality of placing patients on cardiopulmonary bypass and offer a more reliable cure of this arrhythmia compared to catheter-based techniques. Furthermore, this device has the potential to be used endoscopically, allowing for a truly minimally invasive procedure. While these initial results are promising, further studies are clearly needed to examine the chronic effectiveness and safety of these lesions.

ACKNOWLEDGMENTS

The authors would like to acknowledge the major contribution of Jane Gabbard. The technical support of Diane Toeniskoetter, Kathy Fore, and Dennis Gordon was very much appreciated. This work was supported by a research grant from Atricure, Inc. and the following NIH grants: NIH 5 R01 HL32257, NIH T32 HL07275

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