Published in final edited form as:

Med Eng Phys. 2008 May ; 30(4): 454–459.

An electrode array that minimizes blood loss for radiofrequency-assisted hepatic resection

D.J. Schutt¹, A.P. O'Rourke³, J.A. Will⁴, J.G. Webster², D.M. Mahvi³, and D. Haemmerich^{1,5}

¹*Division of Pediatric Cardiology, Medical University of South Carolina, 165 Ashley Ave, Charleston, SC 29425, USA*

²*Department of Biomedical Engineering, University of Wisconsin-Madison, WI, USA*

³*Department of Surgery, University of Wisconsin-Madison, WI, USA*

⁴*Department of Animal Health and Biomedical Sciences, University of Wisconsin-Madison, WI, USA*

⁵*Department of Bioengineering, Clemson University, SC, USA*

Abstract

Hepatic resection is currently the standard treatment for liver cancer. During hepatic resection part of the liver containing the tumor is surgically removed. This type of surgery is accompanied by high blood loss of ~0.6 – 1.35 L. Blood loss is associated with increased complication rates, prolonged hospital stay, and reduced patient survival, especially when transfusion is required. Other researchers have suggested using radiofrequency (RF) or microwave ablation to coagulate a tissue slice before resection to reduce blood loss, but conventional devices typically take several hours. We developed a device consisting of a linear array of blade-shaped, 1 cm wide radiofrequency (RF) electrodes 1.5 cm apart. Bipolar RF power is applied between pairs of adjacent electrodes, leading to high tissue temperatures between the electrodes that promote coagulation of large vessels (>mm) in the resection plane. Rapid switching of applied power between pairs of adjacent electrodes allows simultaneous heating and coagulation of the entire resection plane within 3 – 6 min. In 7 *in-vivo* trials in a porcine model, resection along a plane pre-coagulated with the device resulted in little (<20 mL) to no blood loss, while coagulating all vessels (up to 4.5 mm diameter in this study). Average treatment time (from placement of the device to transection) was 6.8 ± 0.5 min when 4 electrodes were used, and 11.3 ± 1.2 min when 5–7 electrodes were used. This device may reduce blood-loss related morbidity during resection and reduce treatment time by coagulating all vessels in the resection plane.

Keywords

Resection; blood loss; radiofrequency; ablation; liver; coagulation; electrode array

1. Introduction

Despite recent advancements in the efficacy of tumor ablation therapies, surgical resection remains the gold standard for treatment of both primary and metastatic liver cancer ^{1,2}. In a liver resection, either one of the two liver lobes is surgically removed (anatomical resection),

corresponding author: Dieter Haemmerich, 165 Ashley Ave, PO Box 250915, Charleston, SC 29425, Phone: (843) 792 1396, Email: Haemmerich@ieee.org.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

or part of a single lobe is removed (partial resection), depending on tumor location(s). Hepatic resections are associated with a high rate of intraoperative bleeding, with an average blood loss between 600 and 1350 ml^{3,4}. As a result, 28 to 55% of patients undergoing a resection require blood transfusion^{5,6}. Several studies have shown an adverse correlation between blood loss and complication rate, patient survival, and length of hospitalization^{3,6,7}. Similarly, hepatic resections that require blood transfusion have higher complication rates and decreased long-term patient survival rates⁵. The further reduction of intraoperative blood loss (and therefore, a reduction in the number of transfusions) is thus advocated by many surgeons.

Several studies have suggested the use of radiofrequency (RF) or microwave ablation in conjunction with hepatic resection^{8–11}. In this technique, a plane of tissue is coagulated by sequential applications of microwave or radiofrequency energy, using conventional ablation electrodes. Resections performed after thermal coagulation of the resection plane in this fashion exhibit a marked decrease in mean blood loss; one study employing a RF-assisted technique reported a mean blood loss of just 30 ml during partial resections¹⁰. Current limitations associated with these methods are the large number of sequential ablations required to precoatulate the resection plane, and the necessity to individually ligate all vessels larger than ~3 mm. Recently, two specialized devices have become commercially available for RF-assisted liver resection, the Tissuelink Floating Ball device (Tissuelink Medical, Dover, NH) and the Habib 4x device (Rita Medical Systems, Fremont, CA). However, the former device is not capable of coagulating all blood vessels in the resection plane (even with partial vascular occlusion)¹², while the Habib 4x requires a large number of sequential applications, resulting in long treatment times¹³.

Our device applies RF energy in the bipolar mode to adjacent pairs of parallel bladeshaped electrodes in a linear array (Figure 1). Rapid switching of the applied RF energy between single electrode pairs enables simultaneous thermal coagulation of the entire resection plane. We have previously presented preliminary *in-vivo* results using an earlier prototype of this device demonstrating coagulation of a 1.5 cm thick plane of liver tissue in 3 to 6 min¹⁴, which is significantly less time than other RF assisted resection methods. The device was also previously used successfully in a series of porcine *in-vivo* partial nephrectomies¹⁵. In additional preliminary *in-vivo* experiments in the porcine liver, however, we found that not all blood vessels were fully coagulated by the earlier prototype device in all trials. Therefore, we refined the device's power delivery algorithm, and present further *in-vivo* results in this study demonstrating the ability of the device to fully coagulate all blood vessels present in the resection plane of the porcine liver, including quantitative data regarding number and diameter of blood vessels from pre-treatment intraoperative ultrasound scanning.

II. Materials and Methods

Device description

Figure 1 shows the electrode array used in this study. The physical dimensions of the blade electrodes and holder were derived from the dimensions of a typical human resection plane, which is 9 cm deep (max) by 15 cm long. The electrode array consists of ten parallel stainless steel blades held in place by a Teflon holder. Each blade has a sharpened tip to reduce the force required for insertion into the tissue. The blades measure 1 mm by 10 mm and are each 15 cm long. The blade width (10 mm) was designed so that the plane of coagulation would be approximately 2 cm wide. This particular width was selected to allow enough coagulated tissue for effective transection without damaging excess tissue. The blade holder measures 2.5 cm by 3 cm by 16.5 cm. It consists of two blocks of machined Teflon that are held together by three set screws, which allow the user to adjust the clamping force as desired. The spacing between the blades is 1.5 cm, which was derived from computer models¹⁴.

Experimental setup

We apply RF power to the blade electrodes in a bipolar mode. In this mode, a voltage from the RF generator is applied between two adjacent electrodes, resulting in current flow between them and subsequent heating of the tissue in the region between the electrodes due to ionic friction. This differs from the traditional monopolar mode of RF power application, in which current flows from an active electrode in the tissue to a large dispersive electrode located on the skin (typically near the thigh) some distance away from the ablation site. In addition, power application is rapidly switched between adjacent electrode pairs in a repeating sequential fashion with a fixed switching period of 150 ms (see example in Figure 3).

Figure 2 shows a block diagram of the system used in this experiment. We used a PDX 500 (Advanced Energy, Fort Collins, CO, USA) RF generator that can supply up to 500 W of RF power at a frequency of 375 kHz. A Visual Basic program (Microsoft) running on a laptop PC controls the RF generator power P_{gen} by a control signal C_P , and the time period t_n for each electrode pair n by signal C_t via an electronic switch. During each switching cycle, the RF generator power P_{gen} applied to each pair was calculated based on the desired average power for that pair P_n and the number of currently active pairs, N :

$$P_{\text{gen}} = P_n \times N \quad (7)$$

Since each electrode pair is active only $1/N^{\text{th}}$ of the time, N times as much power has to be applied to obtain the desired average power for each pair. Initially, 10 W average power (P_n) was applied to each pair, and then the power for each pair was increased stepwise by 2 W every 8 s. This initial value of P_n and the magnitude of the power increase were determined from preliminary *in vivo* experiments, with the goal of achieving temperatures near 100 °C in the target tissue in ~2 min.

The measured impedance for each electrode pair, Z_n , was calculated during each switching cycle and used to implement an impedance control algorithm similar to those used in commercial ablation systems (to prevent tissue charring and dessication in the region near the electrodes). After 20 s, the program calculated an impedance threshold for each electrode pair, which is 130% of each pair's impedance value at that time (Figure 6). Once Z_n for a particular pair reached its impedance threshold, that pair was left out of the switching cycle for 10 s (i.e. no power was applied to the pair). During this time, the applied RF power continued to switch between the other active pairs, unless Z_n for another pair also exceeded its impedance threshold (in which case it was also left out of the switching cycle for 10 s). After a pair that had reached its impedance threshold had been skipped for 10 s, it was reactivated in the power switching cycle with 30% lower power P_n (to deter further impedance rises for that pair).

In vivo Experiments

Preapproval for animal experiments was obtained from the Institutional Animal Care and Use Committee, University of Wisconsin, Madison. A total of 7 liver lobes were resected from 2 domestic swine (~55 to 60 kg) in this study. The animals were injected intramuscularly with the narcotic preanesthetic Telazol®, anesthetized with inhaled halothane, and intubated via a tracheostomy. The abdominal wall was then incised to allow unencumbered access to the liver. At the conclusion of each experiment, the animals were euthanized by an intracardial injection of potassium chloride.

For each trial, between 4 and 7 blade electrodes were sequentially inserted along the desired resection plane, depending on lobe size. Intraoperative ultrasound (IOUS) was used before each trial to locate and measure all blood vessels in the resection plane that were greater than 2 mm in diameter. IOUS was also used during all electrode insertions to avoid puncturing blood vessels. A custom Teflon template was placed underneath the lobe to prevent puncture or

thermal damage to other organs. Immediately prior to the insertion of the electrodes, hepatic inflow was occluded via the Pringle maneuver, in which the hepatic artery and portal vein were clamped. The total time of power application was dependent on the number of blades employed, since the electronic switch in our prototype device only had 4 channels allowing activation of 4 blades. Thus, for resection planes with 4 blades, power was applied for 3 min. For resection planes with 5 to 7 blades, power was applied to the first 4 blades (3 pairs) for 3 min, followed by the remaining blade pairs for 3 min, for a total power application time of 6 min.

After each trial was completed, the lobe was resected using a scalpel along the distal (in relation to blood flow) electrode edge. After transection, the device was carefully removed from the coagulated edge of the lobe. We then took photographs of each tissue slice using a digital camera and noted which blood vessels measured on IOUS before each trial were not coagulated. ImageJ software (NIH) was then used to determine the total coagulated area of each resection plane from the photographs.

III. Results

All 7 lobes were successfully ablated and resected using our device. The coagulated slice was between 2–3 cm wide. A total of 19 vessels between 2.0 mm and 4.5 mm (median 2.8 mm) in diameter were found in the 7 resection planes using IOUS (Table 1). After transection, none of the vessels exhibited bleeding that required ligation. The total blood loss after transection of each plane was estimated to be <20 mL by the attending surgeon (APO), and was 0 mL in the majority of cases ($n=4$).

Figure 4 shows a representative lobe during one of the procedures, and Figure 5 shows another lobe immediately after transection. In addition to the complete coagulation of all vessels, no bleeding or bile leaks from the liver parenchyma were observed in the regions between the blades in any of the trials. The average time required for each trial and the average area of the coagulated surface for each trial are summarized in Table 2. As previously noted, the time required for the 5 to 7 blade trials was longer because they required two separate 3 min power applications (6 min total).

Figure 6 shows the impedance between and power delivered to a representative pair of electrodes during the course of one of the trials. The average power delivered to each pair during all trials was 18.3 ± 4.1 W and the average maximum power delivered during each trial was 46.0 ± 5.4 W.

IV. Discussion

The use of RF pre-coagulation to reduce blood loss during hepatic resections has become increasingly widespread with two specialized devices now commercially available. Although the reduction in mean blood loss reported by previous studies is encouraging, the techniques and devices employed require several individual applications of RF or microwave energy, with correspondingly long procedural times. In addition, standard RF devices are not able to fully coagulate vessels larger than 3 mm in diameter in the resection plane. To address these limitations, we developed a device capable of thermally coagulating a typical hepatic resection plane in 3 to 6 min, including full coagulation of all blood vessels¹⁴.

The most straightforward method for pre-coagulating a plane of tissue with an electrode array would involve the insertion of the array along the desired plane and subsequent application of RF energy in the monopolar mode to all electrodes simultaneously. This method has several disadvantages. First, commercial clinical RF generators are incapable of supplying enough power to heat the tissue around a large number of electrodes simultaneously. More importantly, prior modeling results have shown that when multiple electrodes are placed in tissue in close

proximity to each other and simultaneously energized, little current flows in the region between the electrodes, and thus little heating occurs there^{14,16}.

For these reasons, we used the bipolar mode of RF power application in our device. This mode has two advantages for this device. First, no ground pads are required since at any time, the RF power ground is connected to one of the electrodes in the tissue, not an electrode on the skin. Ground pad skin burns are already a common complication of clinical monopolar RF ablations (which use a maximum power of 200 – 250 W), and since rapid coagulation of a large tissue slice requires much higher power (up to ~400 W), skin burns below ground pads would be likely if the monopolar mode were used with this device. Secondly, previous computer modeling experiments have shown that bipolar ablation produces higher, more uniform temperatures between adjacent electrodes than monopolar ablation^{14,17}.

Initially, we created computer models where we applied bipolar power to all of the electrodes in the array simultaneously; i.e. the electrodes were all energized simultaneously with alternating polarity (+ polarity, – polarity, +, –, etc.). However, the resulting temperature profile was not uniform between each electrode pair. In addition, this method did not allow independent power regulation between each pair to account for variations in tissue thickness and the presence or absence of heat-sinking blood vessels.

As a result, we investigated the application of bipolar RF power to a single pair of electrodes at a time, rapidly switching the energy delivery to each pair of electrodes in the array in a repeating sequence (Figure 3). This technique takes advantage of the relatively slow time constant of conductive heat transfer in tissue (typically in the range of seconds). If power application is switched sufficiently quickly between electrode pairs, little heat is transferred away from the target tissue during the time when each pair is not energized, and the whole tissue plane can be virtually heated simultaneously. This rapid switching technique has previously been used with monopolar RF energy to create large ablation zones in *ex vivo* tissue¹⁸.

Computer models of this switched bipolar power application algorithm in combination with blade shaped electrodes showed excellent concentration of current density between the electrodes and correspondingly high, as well as uniform, temperatures (see Figure 7)¹⁴. Additionally, since power is delivered to only a single electrode pair at a time, the applied power can be controlled individually for each pair, allowing more uniform heating of the entire tissue plane. In our prior study, power was switched between each pair every 600 ms¹⁴. This time period did not prove to be sufficient to fully coagulate all blood vessels in the resection plane, so in this study we modified the control software to switch the power between the electrode pairs every 150 ms. Since we were able to completely coagulate all blood vessels (up to 4.5 mm diameter) in this study, we believe that this switching period is sufficiently short for the device to be effective in this regard. However, as the number of active electrode pairs is increased (i.e. more than our current prototype's 3 pairs), the amount of time that a given pair will not have power applied to it will increase correspondingly, and the switching time period may need to be reduced to compensate.

To determine the ideal electrode design and spacing for this device, we relied on our previously reported computer modeling results demonstrating that bipolar RF ablation using rectangular, blade-shaped, electrodes produced significantly higher temperatures in the region between adjacent electrodes than standard needle electrodes¹⁴. Additionally, further modeling demonstrated that a 1.5 cm blade separation creates a more uniform ablation zone width than a 2 cm blade separation. The same models suggested that a 1.5 cm blade separation creates a similar ablation zone width as a 1 cm blade separation. Both of these modeling results were verified in preliminary *ex-vivo* and *in-vivo* experiments. We used the 1.5 cm separation in this

study instead of 1 cm because it required fewer electrodes to span a given resection plane (e.g. for a 6 cm long resection plane, 5 electrodes would be required at 1.5 cm spacing, or 7 electrodes with 1 cm spacing), resulting in less tissue trauma during electrode insertion.

We have in a previous study used an earlier prototype to perform partial kidney resection¹⁵. In the current study we applied the device to liver resection in a porcine model. We were able to provide a coagulation plane within 3 min for resection planes that required 4 electrodes or less, and within 6 min (2×3 min) if more than 4 electrodes were required. This is due to a limitation of the current prototype that allows switching between a maximum of four electrodes; a future design may circumvent this limitation. In addition, we were able to coagulate all blood vessels in all seven trials in this study, which were up to 4.5 mm in diameter as measured by IOUS. This is close to the maximum blood vessel diameter expected in human liver resection (~5 mm). We used liver inflow occlusion during this study to ensure coagulation of all vessels, but currently have no data on performance of our device when occlusion is omitted.

While in initial studies tumor ablation electrodes were used to sequentially coagulate small tissue volumes along the hepatic resection plane^{8–11}, recently two commercial devices have become available for this purpose. The Tissuelink device (Tissuelink Medical, Dover, NH) uses a small spherical electrode that is assisted by saline infusion; the electrode is manually moved along the resection plane to dissect tissue while coagulating¹⁹. This is a lengthy procedure and does not allow coagulation of vessels larger than 3mm in diameter even when occlusion is used¹². A second device, the Habib4x (Rita Medical Systems, Fremont, CA) uses two pairs of needle electrodes with 1 cm spacing to precoagulate the resection plane with multiple sequential ablations - typically with blood inflow occlusion. While there is currently no extensive data available on performance of this device, the large number of required applications to create a coagulation plane results in significantly lengthier procedures than the device described in this study¹³.

V. Conclusion

We developed a device that rapidly coagulated the hepatic resection plane in an animal model. Our prototype system was able to coagulate a 2 – 3 cm thick slice of tissue that spanned the length of the resection plane in 3 to 6 min, while successfully coagulating all blood vessels (up to 4.5 mm diameter) in the plane. This device shows promise in the effort to reduce blood loss and operating time during liver and kidney resections.

VI. Acknowledgements

This work was conducted in a facility constructed with support from the National Institutes of Health, Grant Number C06 RR018823 from the Extramural Research Facilities Program of the National Center for Research Resources.

VII. References

1. DeMatteo RP, Fong Y, Blumgart LH. Surgical treatment of malignant liver tumours. *Baillieres Best Pract Res Clin Gastroenterol* 1999;13:557–574. [PubMed: 10654920]
2. Song TJ, Ip EW, Fong Y. Hepatocellular carcinoma: current surgical management. *Gastroenterology* 2004;127:S248–S260. [PubMed: 15508091]
3. Jarnagin WR, Gonen M, Fong Y, DeMatteo RP, Ben-Porat L, Little S, Corvera C, Weber S, Blumgart LH. Improvement in perioperative outcome after hepatic resection: analysis of 1,803 consecutive cases over the past decade. *Annals of Surgery* 2002;236:397–406. [PubMed: 12368667]discussion 406–7
4. Kokudo N, Vera DR, Tada K, Koizumi M, Seki M, Matsubara T, Ohta H, Yamaguchi T, Takahashi T, Nakajima T, et al. Predictors of successful hepatic resection: prognostic usefulness of hepatic asialoglycoprotein receptor analysis. *World J Surg* 2002;26:1342–1347. [PubMed: 12297928]

5. Kooby DA, Stockman J, Ben-Porat L, Gonen M, Jarnagin WR, Dematteo RP, Tuorto S, Wuest D, Blumgart LH, Fong Y. Influence of transfusions on perioperative and long-term outcome in patients following hepatic resection for colorectal metastases. *Annals of Surgery* 2003;237:860–869. [PubMed: 12796583]discussion 869–70
6. Rees M, Plant G, Wells J, Bygrave S. One hundred and fifty hepatic resections: evolution of technique towards bloodless surgery. *British Journal of Surgery* 1996;83:1526–1529. [PubMed: 9014666]
7. Nagasue N, Ono T, Yamanoi A, Kohno H, El-Assal ON, Taniura H, Uchida M. Prognostic factors and survival after hepatic resection for hepatocellular carcinoma without cirrhosis. *British Journal of Surgery* 2001;88:515–522. [PubMed: 11298618]
8. Pellicci R, Pasqualini M, Stella M, Percivale A. Radiofrequency Assisted Liver Resection: A New Technical Device. *Journal of Gastrointestinal Surgery* 2003;7:279.
9. Tabuse K, Katsumi M, Kobayashi Y, Noguchi H, Egawa H, Aoyama O, Kim H, Nagai Y, Yamaue H, Mori K, et al. Microwave surgery: hepatectomy using a microwave tissue coagulator. *World Journal of Surgery* 1985;9:136–143. [PubMed: 3984365]
10. Weber JC, Navarra G, Jiao LR, Nicholls JP, Jensen SL, Habib NA. New technique for liver resection using heat coagulative necrosis. *Annals of Surgery* 2002;236:560–563. [PubMed: 12409660]
11. Zhou XD, Tang ZY, Yu YQ, Ma ZC, Xu DB, Zheng YX, Zhang BH. Microwave surgery in the treatment of hepatocellular carcinoma. *Seminars in Surgical Oncology* 1993;9:318–322. [PubMed: 8210912]
12. Sturgeon C, Helton WS, Lamba A, Chejfec G, Espat NJ. Early experience employing a linear hepatic parenchyma coagulation device. *J Hepatobiliary Pancreat Surg* 2003;10:81–86. [PubMed: 12827477]
13. Ferko A, Lesko M, Subrt Z, Melichar B, Hoffman P, Dvorak P, Vacek Z, Liao LR, Habib NA, Koci J, et al. A modified radiofrequency-assisted approach to right hemihepatectomy. *Eur J Surg Oncol* 2006;32:1209–1211. [PubMed: 16950592]
14. Haemmerich D.; Schutt, DJ.; Will, JA.; Striegel, RM.; Webster, JG.; Mahvi, DM. EMBC 2004. San Francisco: 2004. A device for radiofrequency assisted hepatic resection.
15. Pareek G, Wilkinson ER, Schutt D, Will JA, Warner TF, Haemmerich D, Mahvi D, Nakada SY. Haemostatic partial nephrectomy using bipolar radiofrequency ablation. *BJU International* 2005;96:1101–1104. [PubMed: 16225536]
16. Haemmerich D, Tungjitkusolmun S, Staelin ST, Lee FT Jr, Mahvi DM, Webster JG. Finite-element analysis of hepatic multiple probe radio-frequency ablation. *IEEE Transactions on Biomedical Engineering* 2002;49:836–842. [PubMed: 12148822]
17. Haemmerich D, Wright AW, Mahvi DM, Lee FT Jr, Webster JG. Hepatic bipolar radiofrequency ablation creates coagulation zones close to blood vessels: a finite element study. *Medical and Biological Engineering and Computing* 2003;41:317–323. [PubMed: 12803297]
18. Haemmerich D, Lee FT Jr, Schutt DJ, Sampson LA, Webster JG, Fine JP, Mahvi DM. Large-Volume Radiofrequency Ablation of ex Vivo Bovine Liver with Multiple Cooled Cluster Electrodes. *Radiology* 2005;234:563–568. [PubMed: 15601891]
19. Yim AP, Rendina EA, Hazelrigg SR, Chow LT, Lee TW, Wan S, Arifi AA. A new technological approach to nonanatomical pulmonary resection: saline enhanced thermal sealing. *Ann Thorac Surg* 2002;74:1671–1676. [PubMed: 12440628]

Figure 1. The array of blade electrodes (shown with a full complement of 10 blades). The Teflon block ensures that the spacing between the blades is uniform, and maintains parallel alignment of all blades.

Figure 2.

Prototype system: An electronic switch relays power provided by a commercial RF generator to the currently active electrode pair. Generator output power is controlled by a software algorithm running on a PC, and is dependent on the number of currently active electrode pairs.

Figure 3.

Diagram of rapid switching scheme: in this example with 4 blades (i.e. 3 blade pairs), each pair of adjacent electrodes receives power for 150 ms every 450 ms. After the last pair is energized, power is reapplied to the first pair, and the cycle continues.

Figure 4. A representative lobe during RF power application. Lines were drawn on the surface of the liver to indicate the desired resection plane and the location of large vessels.

Figure 5.

In this particular trial with 6 blades, no bleeding occurred after the tissue was sliced. The area of the coagulated surface in this trial was 15.0 cm².

Figure 6.

The power (dashed line) applied to an electrode pair is increased every 8 s until the measured impedance (solid line) rises above (arrows) the impedance threshold (dotted line), which is calculated 20 s after the start of the trial (as 130% of the impedance value at that time).

Figure 7. Temperature distribution after 3 min ablation in bipolar mode between needle electrodes (left), and blade electrodes (right). Blade electrodes produce significantly higher, and more uniform temperatures. Reproduced with permission from (14).

Vessels coagulated during the 7 trials, sorted by diameter. Each vessel was measured and recorded using IIOUS prior to each trial. For vessel diameters, we report the smallest measured diameter to account for possible non-orthogonality of the vessel to the imaging plane. Lobes 1–3 were from pig #1 and lobes 4–7 were from pig #2.

Pig #	2	2	1	1	2	1	1	1	2	1	2	2	2	2	2
Lobe #	5	7	2	3	4	3	1	3	2	5	6	4	6	7	5
Vessel Dia. (mm)	4.5	4.0	4.0	3.9	3.4	3.4	3.0	2.8	2.8	2.5	2.4	2.3	2.3	2.1	2.0

Table 2

Average procedural time and coagulated surface area for the 7 trials. The device fully coagulated 0.90 and 1.19 cm²/min in the 4 blade and 5 to 7 blade procedures, respectively

No. blades	No. trials	Proc. Time(min)	Area (cm ²)	Coag. Rate cm ² /min
4	4	6.8 ± 0.5	6.0 ± 1.4	0.90 ± 0.10
5 to 7	3	11.3 ± 1.2	13.5 ± 1.3	1.19 ± 0.24