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Radiofrequency ablation with a high-power generator: Device efficacy in an *in vivo* porcine liver model

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Abstract

Purpose: The purpose of this study was to test the feasibility and efficacy of using a high-power generator with nondeployable electrodes to create large zones of coagulation in an *in vivo* porcine liver model.

Methods: With approval from our institution's research animal care and use committee, 12 female swine (mean weight = 55 kg) were anesthetized and received RF ablation at laparotomy. Twenty-nine ablations were performed in four groups using: (i) a conventional 200-W generator and cluster electrode ($n = 4$), or an experimental prototype 250-W generator and (ii) a single, 17-gauge electrode ($n = 9$), (iii) a cluster electrode ($n = 8$) or (iv) three electrodes spaced 2.0 cm apart in a triangular configuration ($n = 8$). In the three-electrode group, power was applied by switching between electrodes using a prototype switching device. All electrodes were internally cooled. Ablation zone size, shape and generator data from each group were compared using a mixed-linear model with animals modeled as random effects.

Results: The high-power generator was able to increase significantly the zone of coagulation. Mean (±SD) ablation diameter was largest in the switched group (4.31 ± 0.7 cm) followed by the cluster (3.98 ± 0.5 cm) and single-electrode (3.26 ± 0.5 cm) groups. Mean diameter in the high-power single-electrode group was no different than the low-power cluster group (3.25 ± 0.4 cm, $p = 0.98$). Circularity measures were high (>0.75) in all groups.

Conclusions: Coupling a high-power generator and switching device is feasible. At higher powers, the switching device creates larger zones of ablation than cluster or single electrodes. Single-electrode ablations created with the prototype high-power generator were equivalent to those produced with the cluster electrode at conventional lower powers.

Keywords: *Radiofrequency (RF) ablation, ablation devices*

Introduction

Radiofrequency (RF) ablation is an increasingly popular technique for the treatment of small- and medium-sized hepatic tumors [1–3]. Treating larger tumors has traditionally involved overlapping several ablation zones to cover the entire tumor volume with a circumferential ablative margin of 1 cm [4]. However, overlapping ablations can be technically difficult and can require long treatment times. Locating residual tumor and repositioning electrodes after an initial ablation can also be very challenging because edema, microbubbles and other postablation tissue changes can make it difficult to distinguish between viable and treated tumor. In addition, Dodd et al. have shown that assuming 3.0 cm diameter single-electrode zones of ablation, tumors up to 3.0 cm in diameter may require as many as 14 overlapping ablations for complete treatment with an ablative margin [4]. It is not technically desirable to place precisely this many overlapping ablations, and the cumulative time to place and ablate serially at several locations may be prohibitively long. Repositioning the RF electrode may also be associated with tumor seeding, which can lead to local recurrence or new tumor growth [5].

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Thus, improved techniques are needed to treat large hepatic tumors.

Nondeployable RF devices such as the Cool-tip^{TM} single and Cluster^{TM} electrodes have traditionally been used with an RF generator that has a maximum output power of 200 W (Valleylab; Boulder, CO, USA). The cluster electrode has been shown to increase the zone of ablation when compared with the single electrode but with a cost of increased invasiveness [6]. Nevertheless, the cluster electrode has been the clinical standard for creating large ablations when with the Cool-tip^{TM} system. In addition, a system was recently developed to allow simultaneous operation of up to three electrodes using a switching device (Switching Controller^{TM}, Valleylab) [7]. The switching system uses tissue impedance feedback to switch between electrodes at impedance spikes (rises in impedance of 25 Ω) or after a 30-s time interval, whichever comes first. Initial experiences in normal porcine liver have shown this system to be effective for creating large volumes of coagulation and treating multiple sites simultaneously [8, 9], and this system is now being used clinically for large and multiple hepatic tumors [10].

It is known that higher applied powers translate into larger zones of coagulation but, to date, nondeployable devices have only been reported with a conventional 200-W generator. It is our hypothesis that coupling the single electrode, cluster electrode and switching system to an experimental high-power generator will increase the zone of coagulation when compared with the current clinical standard, making treatment of large or multiple tumors more effective. Thus, the purpose of this study was to demonstrate the feasibility of combining a high-power RF generator with non-deployable electrodes to create large zones of coagulation in an *in vivo* porcine liver model.

Materials and methods

Financial support and the prototype high-power generator used for this study were provided by Valleylab (Boulder, CO, USA). Authors who were not consultants had control of inclusion of data and information that might present a conflict of interest for authors who are consultants.

Animals and anesthesia

Twelve female domestic swine (mean weight ~55 kg) were used in this study with pre-approval from our institutional research animal care and use committee, and in compliance with all husbandry and experimental studies guidelines outlined by the NIH Guide for Care and Use of Laboratory Animals [11]. Anesthetic induction was achieved with intramuscular tiletamine hydrochloride and zolazepam hydrochloride (Telazol; Fort Dodge, IA, USA), atropine (Phoenix Pharmaceutical, St. Joseph, MO, USA), and xylazine hydrochloride (Xyla-ject; Phoenix Pharmaceutical, St. Joseph, MO, USA). Animals were intubated and anesthesia maintained with inhaled isofluorane to effect (Halocarbon Laboratories, River Edge, NJ, USA). The liver was surgically exposed using a chevron incision and ablations performed as outlined in 'Experimental groups'. A surgical approach was used to ensure accurate placement and visualization of the electrodes while minimizing the number of animals required for the study. After ablations were performed, animals were euthanized with an intravenous solution of pentobarbital sodium and phenytoin sodium (Beuthanasia-D; Schering-Plough, Kenilworth, NJ, USA) and the livers were removed *en bloc*. Zones of ablation were sectioned into ~4-mm slices and optically scanned. One slice from the middle of each ablation zone was selected as a representative slice and immersed in 2,3,5-Triphenyl-2H-tetrazolium chloride (TTC), a stain for mitochondrial activity, to demarcate the zone of complete necrosis.

Experimental groups

Twenty-nine ablations were performed in four experimental groups. Ablations in group 1 ($n = 4$) were performed using a commercially available generator with an output power of 200 W and a three-element cluster electrode (Valleylab), the standard for large-volume ablation with the Cool-tip^{TM} system. Ablations in groups 2–4 were performed with an experimental high-power generator operated at 250 W (Valleylab). The applicator used in group 2 ($n = 9$) was a single 17-gauge electrode; and a cluster electrode was used in group 3 ($n = 8$). In group 4 ($n = 8$), power was switched between three 17-gauge electrodes spaced 2 cm apart in a triangular configuration using a high-power version of the switching system already in clinical use. An acrylic spacer was used to maintain electrode spacing and parallel insertion for the multiple-electrode group (Figure 1). A summary of experimental groups can be found in Table I.

Each ablation was performed for 12 min using the impedance feedback mode to reflect the current clinical recommendation with the Cool-tip^{TM} system. All electrodes were internally cooled using chilled water (input temperature ~4°C) at a flow rate of ~100 ml/min. Multiprong cluster electrodes had an active tip length of 2.5 cm, while single and switched electrodes had an active tip length of 4.0 cm to normalize the total circuit impedance to ~50 Ω,

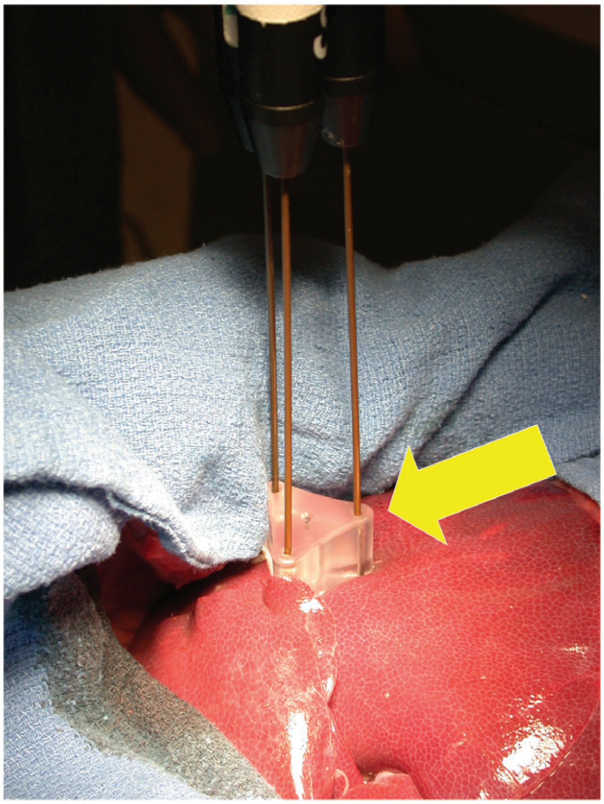

Figure 1. Placement of a three-electrode array in porcine liver. The acrylic spacer (arrow) was used to ensure proper antenna spacing (2.0 cm between all antennas) and parallel insertion.

Table I. Experimental parameters for each group. Active tip lengths were chosen to keep the electrode impedance at ~ 50 Ω in each group.

Group	Sample size	Power (W)	Electrode type	Active tip length (cm)
1	4	200	Cluster	2.5
2	9	250	Single	4.0
3	8	250	Cluster	2.5
4	8	250	3 × single, switched	4.0

which was required to maximize generator output. Each generator had a maximum current output of 2.0 A (200-W generator) or 2.3 A (250-W generator) assuming a 50 Ω load. Using electrodes that create a load impedance higher than 50 Ω would have reduced the applied current. For example, for a 200-W maximum output power, a load impedance of 50 Ω allowed a current of 2.0 A, while a load impedance of 75 Ω could have only allowed a current of 1.63 A. Lower currents are associated with reduced RF heating, so we normalized the impedance of each electrode to reduce errors or bias caused by different electrode designs. In all groups, four grounding pads (two per thigh) were used to reduce the likelihood of skin burns.

Determining coagulation zone size

TTC-stained zones of coagulation were used for measurement and analysis. The stained slice was placed directly onto an optical scanner, saved as an electronic image, and then analyzed using the freeware ImageJ (National Institute of Mental Health, Bethesda, MD, USA). Length along the electrode axis (L), minimum diameter ($D_{\min}$) and maximum diameter ($D_{\max}$) transverse to the electrode axis were all recorded from the unstained zone of complete necrosis. Volumes of coagulation were estimated using the formula for the volume of an ellipsoid:

$$V = \frac{1}{6}\pi D_{\max} D_{\min} L$$

Determining coagulation zone shape

Isoperimetric ratio (IR) of the representative slice was evaluated using the 'Circularity' function in ImageJ. Isoperimetric ratio provides an estimation of circularity in two dimensions, where values near 1 indicate highly circular areas and are most desirable, while values approaching 0 indicate cleft or elongated areas caused by local blood flow or tissue heterogeneities. The appearance of any abnormalities, such as cracked tissue, was also recorded during gross inspection.

Generator electrical data

Electrical data from the experimental high-power generator, such as total energy deposited during the ablation time, generator 'on-time' and average 'on-time' for each electrode, was recorded continuously during each procedure. Total energy was calculated by integrating the power output with respect to time. Generator 'on-time' was determined to be the total time a generator was supplying current to an electrode while average 'on-time' for each electrode was determined by taking the generator 'on-time' and dividing it by the number of electrodes used (3 for the switched group, 1 for all other groups).

Statistical analysis

All groups were compared with respect to length, diameter, volume and circularity of coagulation zones. We used a mixed-linear analysis with animals modeled as random effects to test for differences in size and shape between groups using SAS v9.2 (SAS Institute Inc.; Cary, NC, USA). p-values below 0.05 indicated a statistical significance between groups.

Results

Measurements taken from each experimental group are provided in Table II, while example images demonstrating relative size and shape in each group are shown in Figure 2.

Coagulation zone size comparisons

Ablations performed using the high-power generator showed a substantial increase in size when compared with those using a lower-power generator (Figure 3). In the high-power groups, ablation zones were largest when switched electrodes were used, followed by cluster and single electrodes (Table II). Mean ($\pm$SD) coagulation zone diameters in the high-power switched (4.31 ± 0.70 cm) and cluster (3.98 ± 0.54 cm) groups were significantly larger than with the low-power cluster (3.25 ± 0.44 cm; $p < 0.05$ and $p = 0.005$, respectively). Mean diameters of the high-power switched and cluster groups were also significantly larger than the high-power single group (3.26 ± 0.50; $p = 0.015$ and $p < 0.001$, respectively). The mean diameter of high-power single and low-power cluster groups were nearly identical ($p = 0.98$). When comparing coagulation volumes, the high-power switched group was significantly larger than the all other groups ($p = 0.001$, $p = 0.003$ and $p = 0.011$ for comparison to low-power cluster, high-power single and high-power cluster, respectively).

Coagulation zone shape comparisons

Coagulation zones in the high-power switched group were significantly less circular in cross-section than those from the high-power single or cluster groups ($p < 0.05$ for both comparisons; Figure 4). There were no significant differences in isoperimetric ratio for any other comparisons.

Generator data comparisons

The switched group applied significantly more average power per ablation (246.1 ± 10.7 W) than any other high-power group (118.0 ± 23.1 W for a single electrode, 117.3 ± 13.1 W for a cluster electrode; $p < 0.0001$ for all comparisons). Total 'on-time' in the switched group (10.34 ± 0.6 min) was also significantly longer than any other group (4.88 ± 1.2 min for a single electrode, 4.84 ± 0.8 min for a cluster electrode; $p < 0.0001$ for all comparisons), though the average 'on-time' for each electrode in the switched group was 3.45 min (Table III). Thus, the generator duty cycle (ratio of 'on-time' to treatment time) of the switched group (86.2%) was significantly larger than either the high-power single (40.7%) or cluster groups (40.3%, $p < 0.0001$ for all comparisons).

Other observations

We did not observe any ground pad burns, but in several ablations we noted the appearance of cracks or fissures in the ablated tissue near electrodes, which were filled with coagulated blood (Figure 5). There was no evidence of free intraperitoneal hemorrhage in any case. Overall, some degree of cracking was observed in 59% (17/29) of ablations, with the highest number and percentage appearing in the high-power, single-electrode group (7/9, Table II).

Discussion

To our knowledge, this study is the first to demonstrate feasibility of switching powers greater than 200 W between electrodes and to compare the efficacy of nondeployable electrodes operated above 200 W. We found that using a single, 17-gauge electrode with the high-power generator was equivalent to using the more-invasive cluster electrode with a lower-power generator. High-power switched-electrode ablations were significantly larger than all other groups tested. This leads us to believe that higher-power generators will eventually allow physicians to create larger zones of ablation with less invasive devices.

The prototype multiple-electrode switching system used in this study is nearly identical in operation to the lower-power system now in clinical use. In both systems, a single generator output is connected to the switching device that takes advantage of the inherent 'off-time' in the impedance-controlled pulsing algorithm by switching power to another electrode when the impedance rapidly spikes. This algorithm allows the tissue around the inactive electrodes to rehydrate while another region is heated [12]. In the high-power version presented here, the generator provided a higher output power and the switching components were more robust and well controlled to avoid unwanted harmonic generation while switching. Our results indicate that the significantly higher amount of energy and larger duty cycle provided by the high-power switching system were responsible for generating larger zones of ablation. However, because of the increase in applied power that will need to be dispersed via ground pads, there is a theoretical increase in the risk of ground pad burns. While we did not observe any burns, we did use four ground pads (as recommended for the low-power switching system) to disperse the return current. It is unclear from our study whether additional or improved ground pads will be needed for higher-power operation in clinical practice.

Previous studies have shown that switching between electrodes using lower-power (200 W) is not only feasible, but significantly increases the zone

Table II. Coagulation zone size and shape measurements.

Group	Sample size	Min. diameter (cm)	Max. diam (cm)	Mean diameter (cm)	Length (cm)	Volume (cm^3)	IR	No. ablations with cracking (#/%)
1: 200 W cluster	4	2.80 (0.42)	3.68 (0.55)[a]	3.25 (0.44)[e, f]	3.60 (0.08)	19.56 (5.02)	0.86 (0.10)	2 (50%)
2: 250 W single	9	2.86 (0.48)	3.59 (0.56)[b, c]	3.26 (0.50)[e, a]	4.73 (0.30)	25.70 (7.39)	0.88 (0.05)[f]	7 (78%)
3: 250 W cluster	8	3.43 (0.50)	4.46 (0.60)[d]	3.98 (0.54)	3.48 (0.62)	28.20 (9.02)	0.88 (0.06)[f]	4 (50%)
4: 250 W switched	8	3.41 (0.87)	5.18 (0.76)	4.31 (0.70)	4.50 (0.36)	41.75 (13.98)	0.79 (0.10)	4 (50%)

Note: all values are given as mean (SD). Only statistically significant comparisons ($p < 0.05$) are shown. Comparisons are not given for length or volume because of an inherent bias caused by different electrode lengths.

[a]$p < 0.001$ *vs.* 2.3 A switched; [b]$p < 0.01$ *vs.* 2.3 A cluster; [c]$p < 0.0001$ *vs.* 2.3 A switched; [d]$p < 0.05$ vs. 2.3 A switched; [e]$p < 0.05$ *vs.* 2.3 A cluster; [f]$p < 0.01$ *vs.* 2.3 A switched.

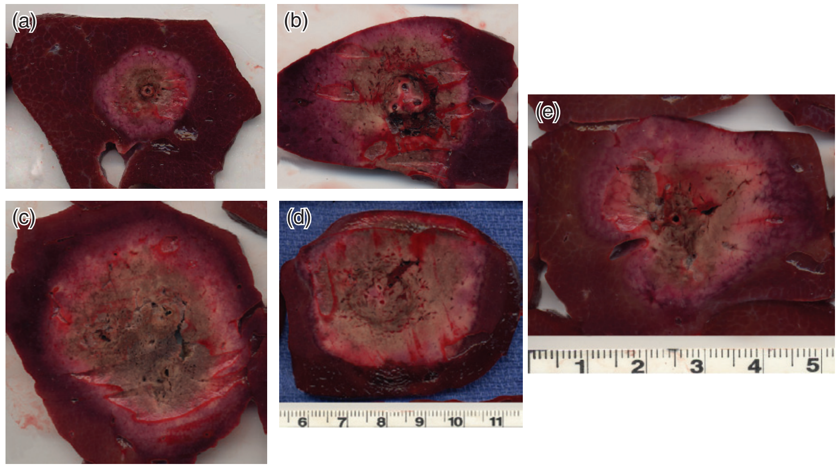

Figure 2. Slices of ablation zones created using a 200-W generator and (a) a single electrode (mean diameter = 2.0 cm) or (b) cluster electrode (mean diameter = 3.0 cm), or using a 250-W generator and (c) single (mean diameter = 2.9 cm), (d) cluster (mean diameter = 4.1 cm) or (e) three switched single electrodes (mean diameter = 5.3 cm).

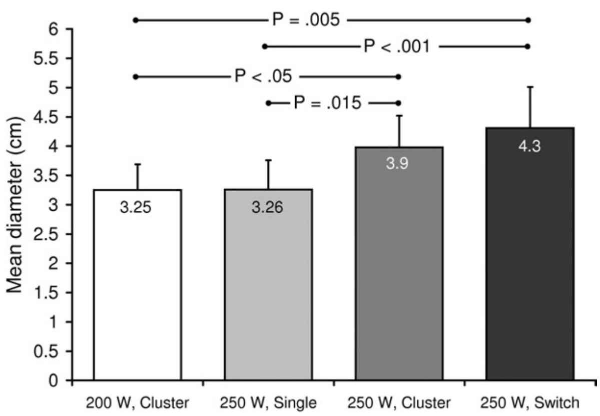

Figure 3. Mean ablation zone diameter for each experimental group. Error bars represent standard deviation.

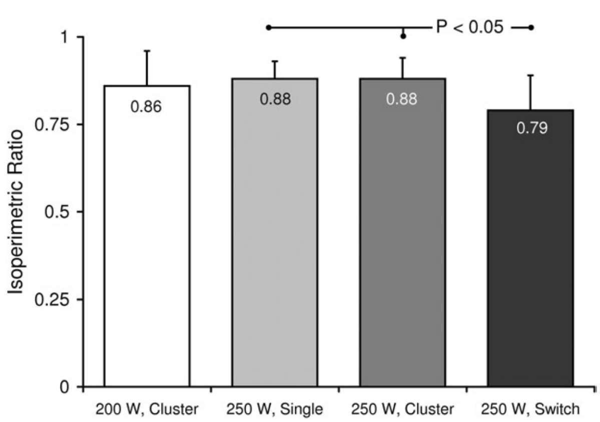

Figure 4. Mean isoperimetric ratio for each experimental group. Error bars represent standard deviation. The drop in IR in the switched group was expected, since the electrodes were placed in a triangular configuration and IR represents how circular a shape is.

Table III. Electrical data recorded from the high-power generator experiments given as mean (SD). The 200-W generator data were not readable at the time of experimentation. All comparisons between either single or cluster groups and the switched group were statistically significant ($p < 0.0001$). There was no statistical difference between single and cluster groups.

Group	Sample size	Average power (W)	Total 'on-time' (min)
2: 250 W single	9	118 (23.1)	4.88 (1.2)
3: 250 W cluster	8	117.32 (16.1)	4.84 (0.8)
4: 250 W switched	8	246.1 (10.7)	10.3 (0.6)

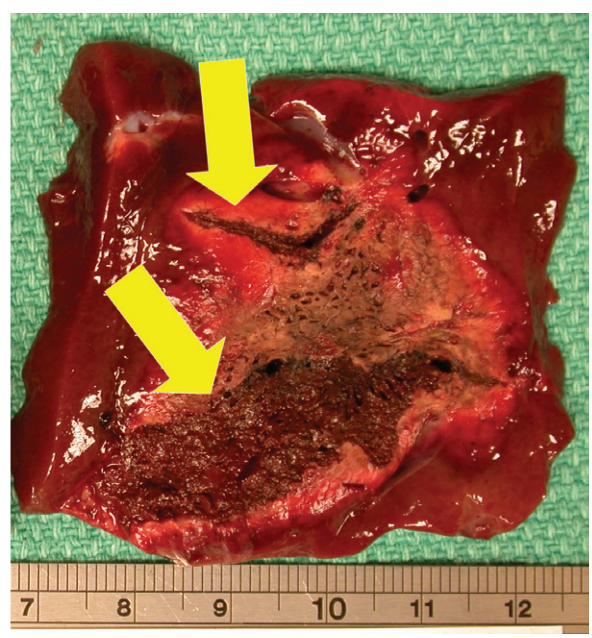

Figure 5. Example of coagulated hemorrhage owing to cracking near electrodes. Note the presence of cracking near at least two of the three electrodes in this case. Hemorrhaging owing to cracking was typically coagulated or self-contained.

of coagulation without the need for overlapping ablations [8]. In addition, it has been shown that by switching between three electrodes one can create three separate zones of ablation that are nearly identical in size and shape to each other and, more importantly, to an ablation created using just one electrode [9]. Whether used in unison or apart, switching between electrodes also offers a significant time saving over sequential overlapping ablations. With these advantages in mind, we have added a high-power generator to show that further increases in ablation zone size are possible. This can be seen when comparing ablations from the present study to those reported using the low-power system: the mean ablation diameter of the switched group in the present study is ~20% larger and more circular than reported in the low-power study [8].

Other options available to increase the ablation zone include the use of multiprong electrodes and multipolar electrodes. Multiprong electrodes like the LeVeen® (Boston Scientific; Natick, MA, USA) and Starburst™ (RITA Medical Systems; Fremont, CA, USA) simultaneously power each prong to spread out the power deposition and increase the zone of ablation. However, these electrodes can be larger in diameter and their deployment requires an additional complexity that can reduce the accuracy of prong placement relative to the tumor. Current also preferentially flows through electrodes in the lowest-impedance medium (blood, urine, etc.), so tissue heterogeneities can cause these types of electrodes to create irregular ablation patterns [13]. Some reports have also cited safety concerns with percutaneous use of multiprong electrodes, particularly when used with saline infusion [14, 15]. Multipolar electrodes are also an attractive option, but tend to heat only the smaller space between the electrodes and, at approximately 14-gauge, are slightly more invasive than the 17-gauge electrodes used in the present study [16, 17].

The appearance of tissue cracking was unexpected. We believe this type of cracking may be due to several factors including rapid heating, outgassing caused by rapid water vaporization, and tissue property changes. The impedance spike used by the pulsing algorithm is caused by rapid dehydration of the tissue immediately surrounding the electrode. Dehydration occurs as water vapor is boiled out of the tissue, escaping as gas. This gaseous escape is responsible for the audible 'pop' frequently encountered during ablation. Dehydration is also associated with mechanical shrinking of the tissue. It is possible that tissue shrinking coupled with a sudden release of water vapor, made even more abrupt by the high powers used, caused enough mechanical stress to lead to sudden cracking. The resulting hemorrhage was self-contained and coagulated in all cases, and was only evident after the ablation zone was removed and sectioned. It is unclear from our study whether this sort of cracking has any effect on long-term safety of the procedure.

Limitations of this study include the use of a normal porcine liver model, use of different active lengths for cluster electrodes and the number of electrodes allowed for switching. At the time of experimentation, there was no large-animal, large-tumor model in the liver. However, Montgomery et al. [18] found that the most significant factor affecting ablation zone size in humans is tumor size. In that study, ablations performed in large human tumors were substantially larger than ablations performed in normal porcine liver in other studies. Thus, we feel the normal porcine liver model adequately predicts (and may underestimate) performance in human tumor. The electrode active lengths used in this study (2.5 cm for clusters, 4.0 cm for single and switched electrodes) were chosen to create a consistent baseline impedance ~50 Ω. As described in 'Materials and methods', this was necessary to ensure that the generator output power was indeed 200 W or 250 W, as prescribed. However, limiting the electrode length to 2.5 cm limits the ablation zone length. Since the length is linearly related to the volume estimation, any limitations on length impose limitations on volume. For this reason, we relied upon ablation zone diameter, rather than volume, to compare groups. Finally, we observed that, because of more rapid heating, there was ~1–2 min of generator 'off-time' when switching with the high-power system. This off-time could potentially be used to power an additional electrode to create larger or more precisely shaped zones of ablation without sacrificing procedure time. Additional development in the switching device is needed for this hypothesis to be tested.

In conclusion, RF ablation with a high-power generator and nondeployable devices is feasible. High power coupled to a single electrode created ablations equivalent to a lower power generator coupled to a clustered electrode but with less invasiveness. Switching between electrodes at high powers created the largest zones of ablation while maintaining a relatively high degree of circularity. More study is needed to evaluate performance in a tumor model, to test whether higher powers or more switched electrodes are feasible and to determine the cause and implications for patient safety of the observed tissue cracking.

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References

1. Lencioni R, Crocetti L, Cioni D, Della Pina C, Bartolozzi C. Percutaneous radiofrequency ablation of hepatic colorectal metastases: Technique, indications, results, and new promises. Invest Radiol 2004;39:689–697.
2. Lencioni R, Cioni D, Crocetti L, Franchini C, Pina CD, Lera J, Bartolozzi C. Early-stage hepatocellular carcinoma in patients with cirrhosis: long-term results of percutaneous image-guided radiofrequency ablation. Radiology 2005;234:961–967.
3. Solbiati L, Livraghi T, Goldberg SN, Ierace T, Meloni F, Dellanoce M, Cova L, Halpern EF, Gazelle GS. Percutaneous radio-frequency ablation of hepatic metastases from colorectal cancer: Long-term results in 117 patients. Radiology 2001;221:159–166.
4. Dodd III GD, Frank MS, Aribandi M, Chopra S, Chintapalli KN. Radiofrequency thermal ablation: computer analysis of the size of the thermal injury created by overlapping ablations. Am J Roentgenol 2001;177: 777–782.
5. Jaskolka JD, Asch MR, Kachura JR, Ho CS, Ossip M, Wong F, Sherman M, Grant DR, Greig PD, Gallinger S. Needle tract seeding after radiofrequency ablation of hepatic tumors. J Vasc Interv Radiol 2005;16:485–491.
6. Goldberg SN, Gazelle GS. Radiofrequency tissue ablation: Physical principles and techniques for increasing coagulation necrosis. Hepatogastroenterology 2001;48:359–367.
7. Lee Jr FT, Haemmerich D, Wright AS, Mahvi DM, Sampson LA, Webster JG. Multiple probe radiofrequency ablation: Pilot study in an animal model. J Vasc Interv Radiol 2003;14:1437–1442.
8. Laeseke PF, Sampson LA, Haemmerich D, Brace CL, Fine JP, Tatum TM, et al. Large volume multiple-probe RF ablation: Results in *in vivo* porcine liver. Radiology 2006;241:116–124.
9. Laeseke PF, Sampson LA, Brace CL, Fine JP, Tatum TM, Winter III TC, Lee Jr. FT. Multiple-electrode RF ablation: Simultaneous production of separate zones of coagulation in an *in vivo* porcine liver model. J Vasc Interv Radiol 2005;16:1727–1735.
10. Laeseke PF, Frey TM, Brace CL, Sampson LA, Winter III TC, Lee Jr. FT. Multiple-electrode RF ablation of hepatic malignancies: Initial clinical experience. Am J Roentgenol 2007;188(6):1485–1494.
11. Institute of Laboratory Animal Research, Commission on Life Sciences, National Research Council. Guide for the care and use of laboratory animals. 1996.
12. Goldberg SN, Stein MC, Gazelle GS, Sheiman RG, Kruskal JB, Clouse ME. Percutaneous radiofrequency tissue ablation: Optimization of pulsed-radiofrequency technique to increase coagulation necrosis. J Vasc Interv Radiol 1999;10:907–916.
13. Pereira PL, Trubenbach J, Schenk M, Subke J, Kroeber S, Schaefer I, Remy CT, Schmidt D, Brieger J, Claussen CD. Radiofrequency ablation: *In vivo* comparison of four commercially available devices in pig livers. Radiology 2004;232:482–490.
14. Steinke K, King J, Glenn D, Morris DL. Percutaneous radiofrequency ablation of lung tumors: Difficulty withdrawing the hooks resulting in a split needle. Cardiovasc Intervent Radiol 2003;26:583–585.
15. Gillams AR, Lees WR. CT mapping of the distribution of saline during radiofrequency ablation with perfusion electrodes. Cardiovasc Intervent Radiol 2005;28:476–480.
16. Clasen S, Schmidt D, Boss A, Dietz K, Krober SM, Claussen CD, Pereira PL. Multipolar radiofrequency ablation with internally cooled electrodes: Experimental study in *ex vivo* bovine liver with mathematic modeling. Radiology 2006;238:881–890.
17. Frericks BB, Ritz JP, Roggan A, Wolf KJ, Albrecht T. Multipolar radiofrequency ablation of hepatic tumors: Initial experience. Radiology 2005;237: 1056–1062.
18. Montgomery RS, Rahal A, Dodd III GD, Leyendecker JR, Hubbard LG. Radiofrequency ablation of hepatic tumors: Variability of lesion size using a single ablation device. Am J Roentgenol 2004;182:657–661.