

# Multiple-electrode Radiofrequency Ablation: Simultaneous Production of Separate Zones of Coagulation in an In Vivo Porcine Liver Model

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**PURPOSE:** A multiple-electrode radiofrequency (RF) system was developed based on switching between electrodes that allows for the simultaneous use of as many as three electrically independent electrodes. The purpose of this study was to determine if each multiple-electrode ablation zone is identical to an ablation zone created with conventional single-electrode mode.

**MATERIALS AND METHODS:** Nine female domestic pigs (mean weight, 90 kg) were used for this study. A prototype monopolar multiple-electrode RF ablation system was created with use of an RF generator and an electronic switching algorithm. A maximum of three electrodes can be used simultaneously by switching between electrodes at each impedance spike (30  $\Omega$  greater than baseline levels). A total of 39 zones of ablation were created at open laparotomy in pig livers with use of a conventional single electrode ( $n = 9$ ), two single electrodes simultaneously ( $n = 6$  ablations; 12 ablation zones), or three single electrodes simultaneously ( $n = 6$  ablations; 18 ablation zones). RF electrodes were spaced in separate lobes of the liver when multiple zones of coagulation were created simultaneously. Animals were euthanized after RF ablation, livers were removed, and ablation zones were sectioned and measured.

**RESULTS:** Zones of coagulation created simultaneously with two or three electrodes were equivalent to ablation zones created with use of conventional single-electrode ablation. No significant differences were observed among control animals treated with a single electrode, those with two separate zones of ablation created simultaneously, and those with three simultaneously created ablation zones in terms of mean ( $\pm$ SD) minimum diameter (1.6 cm  $\pm$  0.6, 1.6 cm  $\pm$  0.5, and 1.7 cm  $\pm$  0.4, respectively), maximum diameter (2.0 cm  $\pm$  0.5, 2.3 cm  $\pm$  0.5, 2.2 cm  $\pm$  0.5, respectively), and volume (6.7 cm<sup>3</sup>  $\pm$  3.7, 7.4 cm<sup>3</sup>  $\pm$  3.8, and 7.8 cm<sup>3</sup>  $\pm$  3.9;  $P > .30$ , analysis of variance, pairwise  $t$ -test comparisons).

**CONCLUSIONS:** A rapid-switching multiple-electrode RF system was able to simultaneously create as many as three separate ablation zones of equivalent size compared with single-electrode controls. This system would allow physicians to simultaneously treat multiple tumors, substantially reducing procedure time and anesthesia risk.

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Abbreviation: RF = radiofrequency

RADIOFREQUENCY (RF) ablation has become an effective treatment for focal tumors of the liver, lung, bone, and kidney (1-4). In many centers, RF ablation is now a standard treatment

option in patients with surgically unresectable malignancies as a result of tumor location and/or number or associated comorbidities that put the patient at high risk with conventional

surgery (5-7). Despite the increasing popularity of RF ablation, there are several major restrictions inherent in commercially available systems that have limited their effectiveness for the treatment of large or multiple widely spaced tumors. Suboptimal generator power and electrical interactions among closely spaced electrodes have limited monopolar RF systems to the use of a single electrode or closely spaced electrode arrays (8-10). Therefore, treating a large tumor or several small tumors requires multiple consecutive placements of a single RF electrode (11). This increases treat-

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ment time and the technical complexity of RF procedures. In addition, microbubbles, bleeding, and edema from preceding electrode placements and tissue heating can substantially decrease visualization of untreated tumor (12). This can make subsequent electrode placements very difficult, which may increase local tumor progression. Given local recurrence rates as high as 50% (13–15), a multiple-electrode system may substantially improve outcomes in selected patients.

A prototype multiple-electrode RF system has been developed based on switching between electrodes with use of impedance control. This system has been shown to create large, conglomerate zones of ablation when the electrodes are placed in close proximity to one another (10). However, if multiple tumors are to be simultaneously ablated in remote locations in the liver, it is axiomatic that each electrode must reliably produce a zone of ablation similar in size and shape to a single electrode running in conventional mode.

The purpose of this study was to determine if multiple-electrode ablation zones created simultaneously in separate parts of porcine liver are equivalent to one another and to those created with use of conventional (ie, sequential) technique. If no differences between zones of coagulation are found, it will be possible to use this type of system to concurrently treat multiple tumors, regardless of location. This may decrease procedure time, technical complexity, and anesthesia time associated with RF ablation, likely resulting in decreased complications.

## MATERIALS AND METHODS

### Animals, Anesthesia, and Procedures

Nine female domestic swine (mean weight, 90 kg) were used for this study. Preapproval was obtained from the research animal care and use committee of our institution, and all husbandry and experimental studies were compliant with the National Institutes of Health Guide for Care and Use of Laboratory Animals (<http://oacu.od.nih.gov/regs/guide/guidex.htm>). Anesthetic induction was achieved with intra-

muscular tiletamine hydrochloride and zolazepam hydrochloride (Telazol; Fort Dodge Animal Health, Fort Dodge, IA), atropine (Phoenix Pharmaceutical, St. Joseph, MO), and xylazine hydrochloride (Xyla-Ject; Phoenix Pharmaceutical). Animals were intubated and anesthesia was maintained with inhaled isoflurane (Halocarbon Laboratories, River Edge, NJ) to effect. A chevron incision was used to surgically expose the liver. Multiple RF ablations were performed in separate liver lobes (one per lobe). Animals were then euthanized with an intravenous overdose of pentobarbital sodium and phenytoin sodium (Beuthanasia-D; Schering-Plough, Kenilworth, NJ). The zones of coagulation were excised and sectioned at intervals of approximately 4 mm.

### Study Groups

A commercially available RF generator (Cool-tip RF ablation system; Valleylab, Boulder, CO) was used to create 39 zones of coagulation in nine pigs. Group 1 (nine ablations, nine zones of ablation) consisted of single control zones of ablation created one at a time with use of conventional technique, whereas the other groups consisted of two or three RF ablation zones created simultaneously. Zones of ablation were created two at a time in group 2 (six ablations, 12 zones of ablation) and three at a time in group 3 (six ablations, 18 zones of ablation). A single control ablation and an ablation from group 2 ( $n = 3$  pigs) or group 3 ( $n = 6$  pigs) were performed in each animal. A prototype switching system was used to create the ablation zones in groups 2 and 3.

### Conventional single-electrode RF ablation

All control RF procedures described in this study were performed with the Cool-tip RF ablation system (Valleylab). The system includes a 480-kHz monopolar RF generator that operates at a maximum of 200 W (2.0 A at 50  $\Omega$ ). The generator uses an impedance feedback loop to maximize energy delivery by minimizing charring (16). Tissue charring is limited by circulating chilled sterile water (approximately 18°C–20°C at the electrode tips) through the electrodes during the

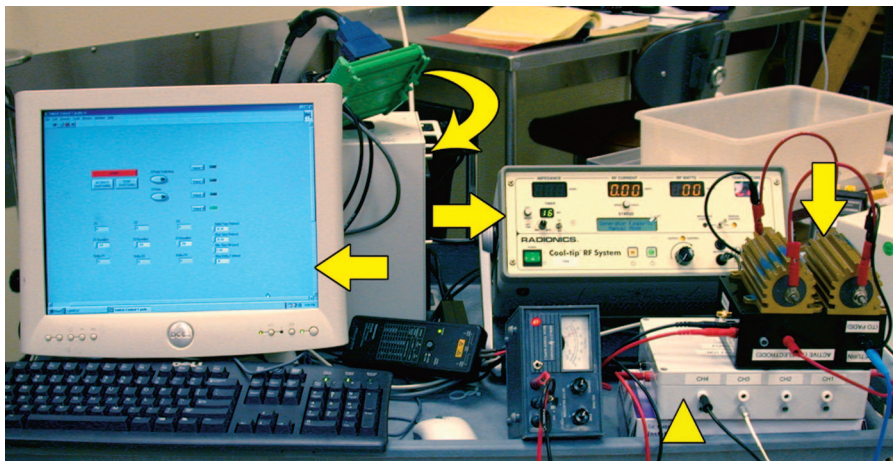
ablations by way of a peristaltic pump (Model PE-PM; Valleylab). The single RF electrodes are 17 gauge (1.5 mm) in diameter with a 3.0-cm exposed tip. Single ablation zones were created by applying power for 12 minutes per ablation according to the manufacturer's recommendations.

### Experimental multiple-electrode RF ablation

All multiple-electrode RF procedures described in this study were performed with use of a prototype two- or three-electrode monopolar RF ablation system (Fig 1) based on switching between electrodes (10,17,18). Power from the RF generator was initially relayed to one of the electrodes via the electronic switch. Power was then switched from one electrode to the next when a sharp increase in impedance was detected (ie, when the impedance level reached 30  $\Omega$  greater than its baseline value). If the system cycled too quickly, such that an electrode was reactivated without being off for at least 5 seconds, power was diverted to a 150- $\Omega$  resistor for the remainder of the 5 seconds to allow the tissue impedance to decrease. Multiple-electrode ablation zones were created by placing two or three electrodes in different lobes (right lateral, right medial, left medial, or left lateral) of the liver and applying power. A total of 13 minutes of ablation was selected for the multiple-electrode system. The time required to initially activate the last of the three electrodes was approximately 1 minute (during which time the other two electrodes were in the "off" position). Therefore, each of the three electrodes in the multiple-electrode system had the opportunity to be activated for a total of 12 minutes.

### Measurement of Ablation Zone Size and Shape

Zones of ablation were excised and lengths were measured with calipers. Ablation zones were then sliced perpendicular to the electrode axis at intervals of approximately 4 mm. Slices were optically scanned (Perfection 2450 Photograph Model G860A; Epson, Long Beach, CA) and saved as electronic images. The ablation zone size was analyzed with use of ImageJ



**Figure 1.** Photograph of prototype multiple-electrode RF ablation system. The system is controlled by a software-implemented controller (curved arrow). The user interface is marked by the left arrow. The RF generator (right arrow) provides the RF energy and monitors the impedances of the three electrodes. The energy is relayed to one of the electrodes or the load (150- $\Omega$  resistor, low arrow) via the electronic switch (arrowhead).

software (National Institute of Mental Health, Bethesda, MD). Ablation zone measurements were taken with use of the central white zone of complete necrosis, not the surrounding red zone that has been shown to contain viable cells (12,19–21). Ablation zone volumes were calculated according to the formula for the volume of an ellipsoid:

$$\frac{4}{3} \pi abc$$

where  $a$ ,  $b$ , and  $c$  are the length axis radius, width axis radius, and height axis radius, respectively. Ablation zone length, minimum diameter, and maximum diameter were used for these values in our study.

The isoperimetric ratio was used to estimate ablation zone shape. This ratio gives an estimation of roundness in two dimensions (20,22). It was calculated with use of a representative slice to measure minimum and maximum diameters. The closer the value is to one, the more round the ablation zone shape. The isoperimetric ratio is calculated according to the following formula:

$$R = \frac{4\pi A}{p^2}$$

where  $A$  indicates area and  $p$  indicates perimeter.

### Statistical Analysis

Single-electrode (ie, conventional) and multiple-electrode RF ablation zones were compared with respect to size and shape. Analysis of variance was used to test for overall differences in isoperimetric ratio and mean minimum diameter, maximum diameter, length, and volume of coagulation among the different ablation techniques. Two-sample  $t$ -tests were performed for pairwise comparisons between groups for each dimension. Bonferroni correction, a more stringent cutoff, was used because of the high number of tests being performed ( $4^5 = 20$ ), yielding a cutoff of  $0.05/20 = .004$ . In addition to these test results, differences among groups were quantified with the percent difference between the averages for pairs of techniques. Percent difference is defined as the absolute difference between two averages divided by their average.

Finally, the uniformity of coagulation was assessed for each of the experimental groups by comparing measurement standard deviations between groups as well as analyzing the variability within multiple-electrode groups. The variability within multiple-electrode groups can be broken down into two components: (i) interablation variability, ie, the variability among the multiple-electrode ablations in each experimental group; and (ii) intraablation variability, ie, the

variability within each multiple-electrode ablation. For example, the variability within group 2 consisted of (i) the variation among the six pairs of ablations and (ii) the variation within each pair of ablations. A linear regression model with a binary covariate was fit and the resulting  $r^2$  (between 0 and 1) gave the percentage of the total variation within each experimental group explained by interablation variation. The intraablation variation relative to the total variation is calculated as  $1 - r^2$ .

## RESULTS

### Ablation Zone Size Comparison

Mean ( $\pm$ SD) minimum diameter, maximum diameter, length, and volume of coagulation are given in **Table 1** and depicted in **Figure 2**.  $P$  values on analysis of variance and maximum differences between mean values (given as the absolute value and as a percentage of the average SD) are also listed. When comparing ablation zones created with use of conventional single-electrode RF versus two- and three-electrode RF, none of the  $P$  values were statistically significant at the usual threshold of .05 or the corrected threshold of .004. It should be noted that the maximum differences between groups for minimum diameter, maximum diameter, and length were all less than 3 mm, or approximately half the SDs.

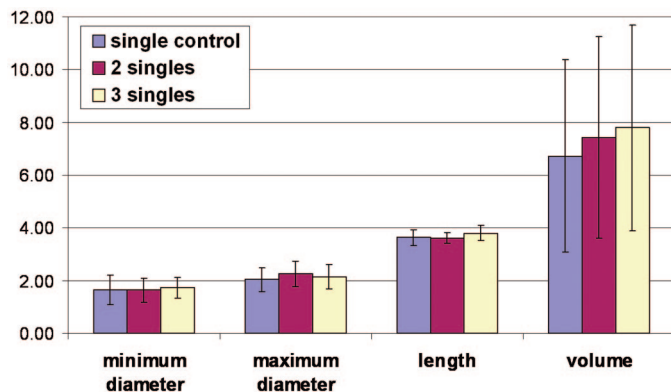
The percent differences (given in decimal form) can be found in **Table 2**. The differences were all less than 15%. Moreover, the largest differences corresponded to multiple-electrode ablation zones having larger values than the single-electrode controls, which indicates that the multiple-electrode algorithm may create somewhat larger ablation zones than the conventional single-electrode mode. However, these results are not statistically significant based on the analysis performed.

**Figure 3** shows the distribution of average diameters for each of the ablation zones. The average diameters were calculated as the average of the minimum and maximum diameters and meant to serve as an index for ablation zone size when comparing the distribution of ablation zones among groups. In summary, the prototype multiple-electrode RF ablation

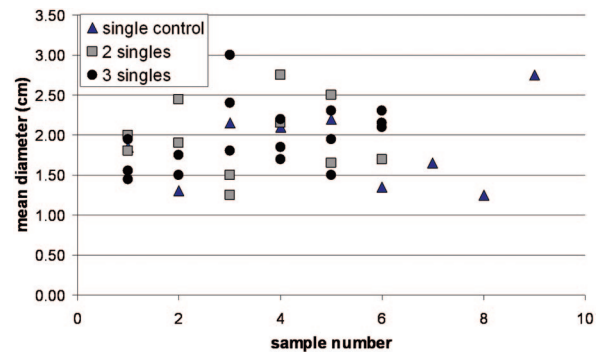
**Table 1**  
RF-induced Coagulation Dimensions and Volume

Group	No. of Ablation Zones	Minimum Diameter (cm)	Maximum Diameter (cm)	Length (cm)	Volume (cm <sup>3</sup> )	Isoperimetric Ratio
Single	9	1.6 ± 0.6	2.0 ± 0.5	3.6 ± 0.3	6.7 ± 3.7	0.78 ± 0.15
Two singles	12	1.6 ± 0.5	2.3 ± 0.5	3.6 ± 0.2	7.4 ± 3.8	0.81 ± 0.07
Three singles	18	1.7 ± 0.4	2.2 ± 0.5	3.8 ± 0.3	7.8 ± 3.9	0.76 ± 0.09
ANOVA <i>P</i> value	—	0.83	0.58	0.12	0.79	0.40
Maximum mean difference	—	0.1	0.3	0.2	1.1	0.05
Percent of SD	—	20	60	75	29	16

Note.—*P* > .05 for all pairwise comparisons. Values are given as means ± SD where applicable. Percent of SD is the maximum mean difference divided by the average SD.



**Figure 2.** Comparison of ablation zone size created with each of the three protocols. Note that no differences were seen among the three groups in any dimension. Minimum diameter, maximum diameter, and length are given in centimeters. Volume is given in cm<sup>3</sup>. Error bars represent SDs.



**Figure 3.** Distribution of average diameters for individual zones of ablation. Sample numbers correlate to the order in which the ablation zones were created within the groups. There is no correlation between ablation zones with the same sample number in different groups. For example, sample 1 corresponds to the first single control ablation zone, pair of two ablation zones, or triplet of three ablation zones created. Note that there were nine single ablation zones, six pairs of ablation zones, and six triplets of ablation zones created.

system created ablation zones with mean minimum and maximum diameters, lengths, and volumes greater than or equal to those created one at a time in the conventional fashion.

#### Ablation Zone Shape

Mean isoperimetric ratios for each of the groups are listed in **Table 1**. No statistically significant differences in isoperimetric ratio were seen among groups. The percent differences for all comparisons were less than 10% for isoperimetric ratios. **Figure 4** shows one representative ablation zone from each of the three groups. **Figure 5** shows three ablation zones created simultaneously.

#### Uniformity of Multiple-electrode Zones of Ablation

The uniformity of ablation zone size and shape was similar among ablation groups. No significant differences were seen between the SDs of ablation zone measurements for the three groups (**Table 1**). **Table 3** gives the intraablation variability for multiple-electrode zones of coagulation. The intraablation variability is approximately 30%–60% of the total variability, and is similar for two- and three-electrode groups for minimum diameter, length, and volume. Noticeable differences between the two- and three-electrode groups were seen for maximum diameter (0.29 cm vs 0.56 cm) and isoperimetric ratio (0.65 vs

0.24). No clear trends were evident among the measurements.

#### DISCUSSION

This study demonstrates that it is feasible to concurrently ablate at least three separate volumes of tissue with currently available RF generators with use of an impedance-controlled multiple-electrode RF system based on switching. No statistically significant differences were found among the different methods. Maximum differences between groups for mean minimum diameter, maximum diameter, and length were all less than 3 mm, or approximately half the SDs. These differences are negligible from a practical point of view given that imaging res-

**Table 2**  
Percent Differences in Ablation Areas

Comparison	Minimum Diameter (cm)	Maximum Diameter (cm)	Length (cm)	Volume (cm <sup>3</sup> )	Isoperimetric Ratio
Single/two singles	0.6	10.2	0.0	9.9	3.7
Single/three singles	5.3	5.7	5.1	14.9	2.6*
Two singles/three singles	5.9	4.5	5.1	5.0	6.4

\* Mean isoperimetric ratio of single to 3 singles. For all other comparisons, ablation parameter is greater for multiple-electrode group than single-electrode group. Note.—Percent differences are defined to be the difference in the averages for the two groups divided by the average of their means.

olution is only within 2–3 mm. The variability of ablation zone dimensions (ie, SD or variance) was comparable between the multiple-electrode groups and the single-electrode group. In other words, performing ablations simultaneously resulted in zones of coagulation with similar size, shape, and variability in size and shape to ablation zones created one at a time (ie, sequentially).

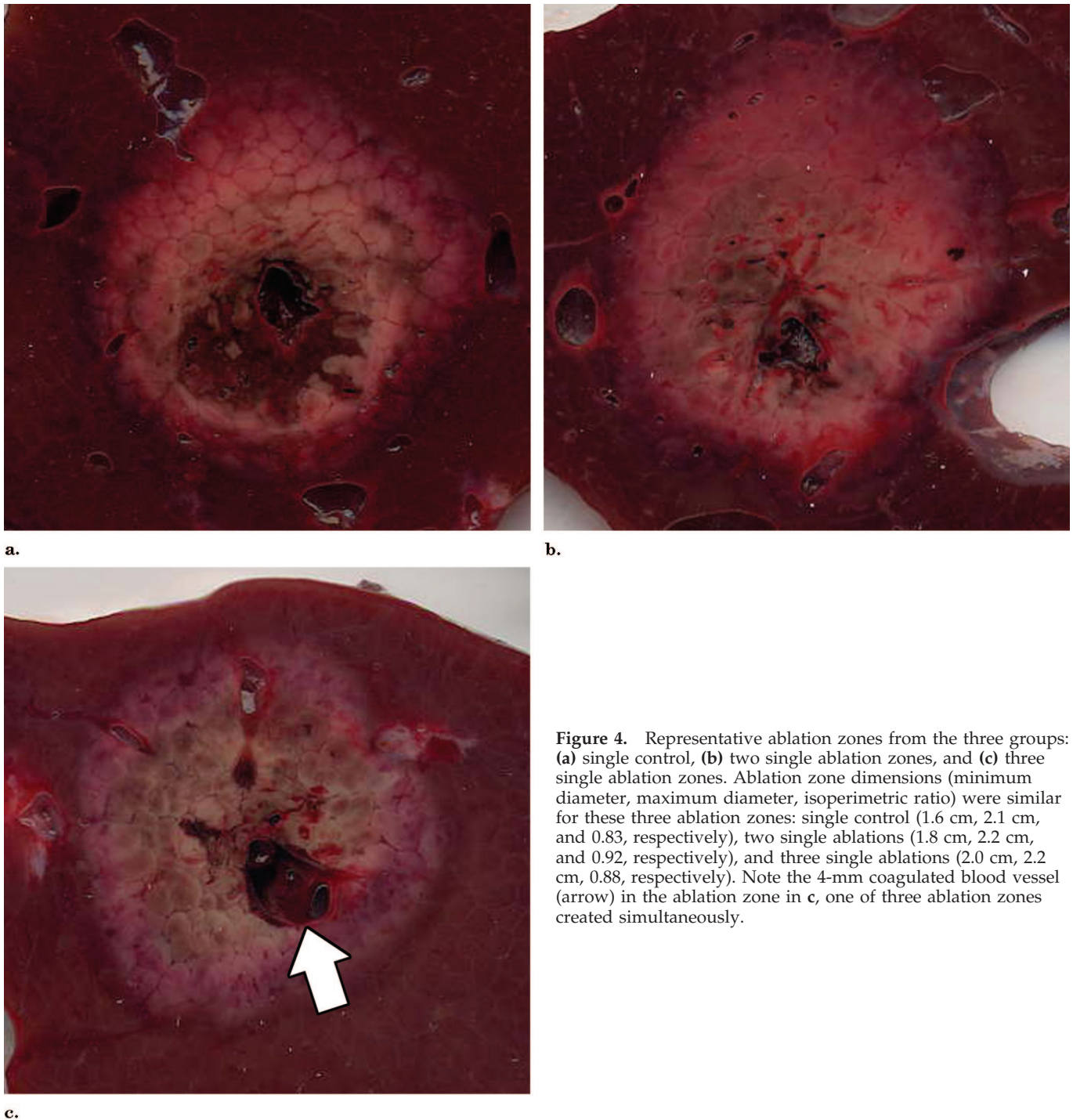
The variability of ablation zone metrics for the multiple-electrode groups was broken down into two components: intraablation and interablation. The intraablation variability describes the variation between simultaneously created ablation zones and was generally less than the interablation variability, which describes the variation between animals. Therefore, the variation in ablation zones is caused to a greater extent by differences between animals than by the use of the multiple-electrode system within an animal. Clinically, this implies that patient-to-patient differences are more important than differences within the same person. However, it should be noted that the overall variability (both components added together) for the multiple-electrode groups is similar to that in the single-electrode group. In other words, the variability seen with the multiple-electrode system is comparable to that seen with the current single-electrode system. Finally, tumor size has been shown to influence the resulting ablation zone size and shape (23). Clinical trials are needed to determine the combined effect of tumor characteristics and multiple-electrode application on the resulting ablation zones, especially for the cases in which we observed great intraablation to inter-

ablation variability and a large discrepancy between RF ablation with two and three electrodes (maximum diameter and isoperimetric ratio).

The concept of simultaneous creation of multiple zones of ablation with RF is not new. Arrays of RF applicators have been used in clinical hyperthermia (24,25). In addition, Goldberg et al (8,9) have performed several studies to investigate the performance of multiple simultaneously activated electrodes. Both these studies demonstrated the importance of interelectrode distance with the use of multiple electrodes. At greater distances between electrodes, multiple discrete ablation zones are created, whereas electrodes placed in close proximity to one another create large, confluent areas of necrosis. This is the basis for the cluster electrode (Valleylab), which consists of three single electrodes in a triangular configuration spaced 5 mm apart. The three electrodes of a cluster electrode are attached to a single handle and are driven in parallel. Therefore, a cluster electrode behaves like a single larger electrode. In contrast, the system described in this article consists of three electrically independent electrodes that are temporally switched such that each electrode receives the full generator power when activated. When available generator power is split among simultaneously activated electrodes (as is the case with a cluster electrode), each electrode receives only a fraction of the maximum generator power ( $1/n$ , where  $n$  is the number of electrodes). Therefore, as many as  $n$  times the power of current systems would need to be applied for each electrode to perform as well as in single-electrode systems. Because commercially available

RF systems use a maximum of 250 W of power, systems with as much as 750 W of power would be necessary to power three electrodes. Higher-power RF generators are not currently available, in part because of the increased risk of grounding pad burns as a result of more current being delivered than could be recovered by conventional pads without heating (26).

In this study, each electrode was activated at full power until a rapid increase in impedance was encountered, followed by switching to the next electrode. Activating one electrode at a time eliminates the need to split power among electrodes, allowing higher power and current density at each electrode tip. In addition, it has been shown that pulsing energy deposition results in larger ablation zones (16), most likely by limiting charring and allowing tissue rehydration, both of which decrease impedance. Therefore, pauses between consecutive electrode activations are necessary for optimal performance. The multiple-electrode system design takes advantage of the impedance control mode of the Cool-tip system to maximize current application to each electrode, regardless of impedance or location. When in conventional (ie, single-electrode) impedance mode, the generator powers an electrode until impedance increases to 10  $\Omega$  greater than baseline levels and causes tissue boiling and dehydration. At this point, the generator switches off power for 15 seconds, or until the impedance returns to baseline level. As the zone of coagulation reaches maximum size, the generator generally spends less time in the "on" position and more in the "off" position. Therefore, the generator duty cycle decreases throughout the course of the ablation. The switched system described in this study takes advantage of the inherent "off" time of the optimized pulsing algorithm to power additional electrodes. At some theoretical limit, the addition of more electrodes to the system will result in decreased performance at each electrode site unless higher generator powers are used. As shown in this study, this limit has not yet been reached when powering three electrodes. Because of the complexity of placing and monitoring more than three separate zones of ablation, we have not yet created a device with four or more electrodes,



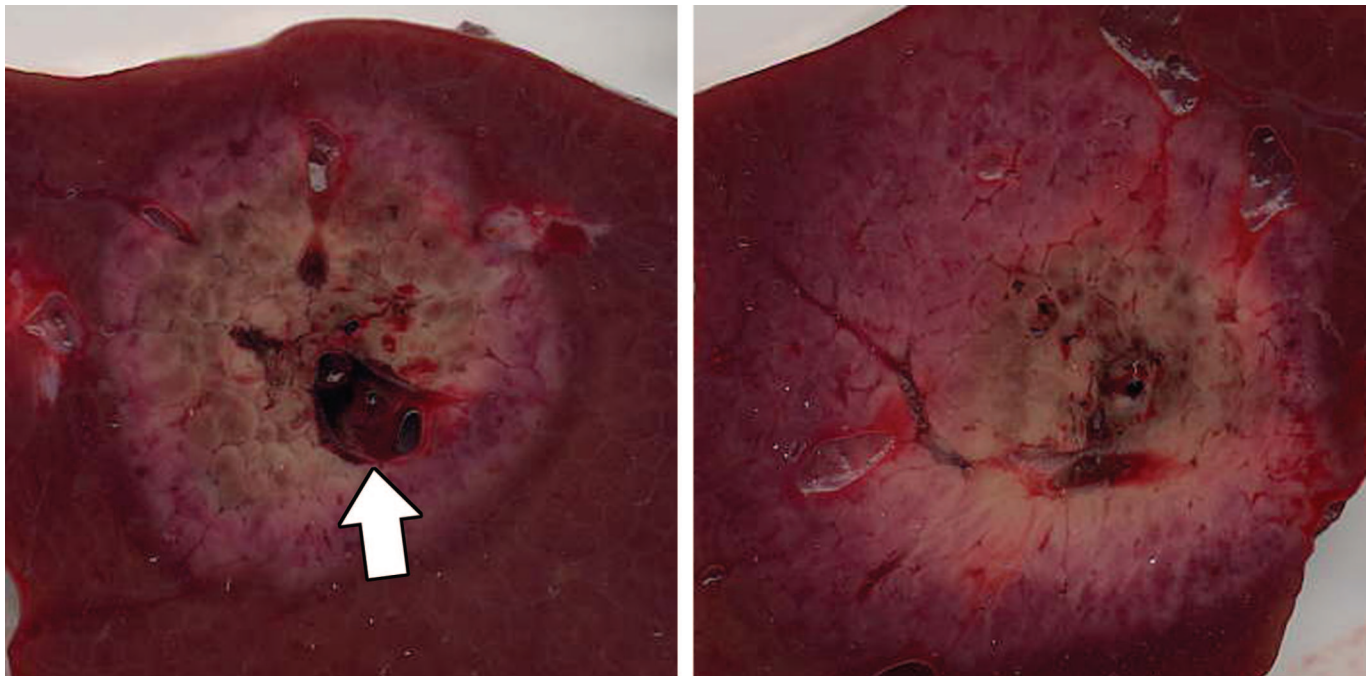
**Figure 4.** Representative ablation zones from the three groups: (a) single control, (b) two single ablation zones, and (c) three single ablation zones. Ablation zone dimensions (minimum diameter, maximum diameter, isoperimetric ratio) were similar for these three ablation zones: single control (1.6 cm, 2.1 cm, and 0.83, respectively), two single ablations (1.8 cm, 2.2 cm, and 0.92, respectively), and three single ablations (2.0 cm, 2.2 cm, 0.88, respectively). Note the 4-mm coagulated blood vessel (arrow) in the ablation zone in c, one of three ablation zones created simultaneously.

but when higher-power generators become available that more rapidly produce impedance spikes (and thereby increase "off" time), it may be possible to increase the number of electrodes to greater than three without sacrificing electrode performance.

In the past, a related multiple-electrode RF ablation system was created

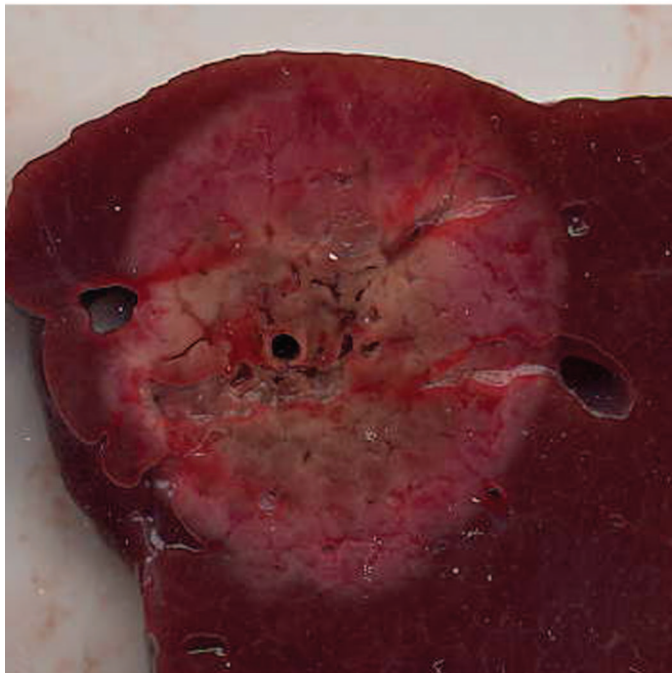
that was able to produce two ablation zones simultaneously with use of a multiple-prong RF device (27). This system used temperature control to power the electrode at the lowest mean temperature until a target temperature was reached. Compared with

the current impedance-controlled algorithm, it is unlikely that a temperature-controlled device will be able to power more than two electrodes simultaneously without a substantial decrease in system performance. In contrast to the impedance-controlled system, the temperature-controlled



a.

b.



c.

**Figure 5.** Three single ablation zones created simultaneously with use of the switching algorithm. Note the similar ablation zone dimensions. The minimum diameters for ablation zones in a, b, and c were 2.0 cm, 2.2 cm, and 1.9 cm, respectively. The maximum diameters were 2.2 cm for the ablation zone in a and 2.4 cm for ablation zones in b and c. The isoperimetric ratios for the three ablation zones were 0.88, 0.82, and 0.78, respectively. The ablation zone in a has a 4-mm coagulated blood vessel (arrow) within it.

device was always in the “on” position, powering the lower-temperature electrode. Therefore, further gains in performance are unlikely until higher-power generators become available. In addition, driving a single electrode to an impedance spike has advantages for overall system performance as

rapid increases in impedance are associated with vascular thrombosis (28). This decreased tissue perfusion makes it less likely that the tissue surrounding an RF electrode will substantially cool when the generator is powering another electrode.

The ability to simultaneously pro-

duce multiple zones of ablation would be advantageous for the treatment of several different tumor types. For example, most hepatic metastases from colorectal cancer (or from any primary tumor) are not solitary (29,30). Hepatocellular carcinoma often presents with multiple tumors as a result of the

**Table 3**  
Multiple-electrode Ablation Intraablation Variability\*

Group	Minimum Diameter	Maximum Diameter	Length	Volume	Isoperimetric Ratio
Two single electrodes	0.45	0.29	0.23	0.37	0.65
Three single electrodes	0.44	0.56	0.36	0.48	0.24

\* Values are given as  $1 - r^2$ , which quantifies the intraablation variability relative to the total variability within the experimental group. For example, the variability in minimum diameter between three ablation zones created simultaneously was approximately 44% of the total variability seen within the three single electrode group.

diffuse nature of cirrhosis (31). Neuroendocrine tumor metastases to the liver are often multiple and symptomatic. Debulking with RF ablation has been shown to increase the quality of life in these patients (32), but ablating a large number of tumors with current RF technology in one session so that the patient has only a small amount of residual tumor volume may be prohibitive in terms of treatment time. Simultaneous treatment of multiple tumors would be possible with this system.

Currently, other tumor ablation modalities competitive with RF ablation have multiple-electrode capability. Cryoablation and microwave ablation are able to create large conglomerate zones of ablation or ablate multiple tumors simultaneously with use of multiple applicators (27,33,34). The two commercially available cryoablation systems in the United States—the Cryocare (EndoCare, Irvine, CA) and SeedNet (Galil Medical Systems, Wallingford, CT) devices—have the capability to support eight and 30 probes, respectively.

A major limitation to the use of RF ablation is the large amount of time necessary to ablate all but the smallest tumors. Although we are not aware this has been formally studied, hepatic RF ablation in our clinical practice often lasts longer than 3 hours. Although much of the time spent on an ablation is devoted to patient positioning, anesthesia, and scanning, substantial time is also required to place electrodes and perform consecutive (rather than simultaneous) ablations. Initial placement of all electrodes before any ablation and simultaneous treatment of multiple tumors should help decrease these prolonged procedure times.

The costs associated with RF ablation are a combination of physician and assistant time, anesthesia, room time, and disposable product use. A case requiring multiple RF electrodes rather than a single electrode would increase the cost of disposable items, but may decrease other procedural costs associated with the time of the procedure. Therefore, multiple-electrode RF ablation may ultimately decrease the overall cost of the procedure. In addition, the ability to decrease procedure time will help free physicians, technologists, and nurses to attend to other cases. Whether multiple-electrode RF ablation ultimately results in a net cost savings is beyond the scope of this study, but formal analysis of the economic impact of this technology may be warranted in the future.

The main limitation to our study is the use of an animal model with normal liver rather than a tumor model or human clinical trial. Factors such as tumor size and tissue properties may alter the size of the ablation zone for different simultaneously treated tumors (23,35). Nevertheless, it is important to establish the potential uniformity that can be achieved under optimal conditions in homogeneous tissue, and the animal model is sufficient for this purpose. Most human liver tumors are less vascular than normal porcine liver; therefore, electrode performance is usually superior in tumors compared with normal liver as a result of a decreased heat-sink effect created by large hepatic and portal veins. Therefore, although the ablation zones created in this study are too small to treat most tumors if an adequate margin is to be achieved, absolute ablation zone size in a tumor environment will likely increase and

will need to be determined in human clinical trials.

An additional limitation is the lack of data with use of more than three RF electrodes in simultaneous mode. We believed such investigation was unnecessary because it has been our experience that greater numbers of widely spaced electrodes are difficult to place and monitor in different areas of the liver, particularly in a percutaneous environment. However, given the fact that the RF ablation zones created with three electrodes simultaneously were slightly larger (albeit not significantly so) leads us to believe that the “off” times associated with multiple-electrode ablation may be too short. Based on this finding, four- or five-electrode systems may be possible at 200 W of power without decreasing individual electrode performance, and as higher power generators become available in the future, this should certainly be the case.

Finally, to formally demonstrate equivalence, a statistical test of equivalence would need to be formulated to some tolerance, as described by Friedman et al (36). However, such tests are known to have low power and generally require a larger sample size than was feasible for this study.

In summary, we have demonstrated that multiple-electrode RF ablation with use of switching technology can be performed without loss of individual electrode performance when the electrodes are widely spaced. This may help to substantially decrease procedure time, leading to a concomitant decrease in costs and complications related to the lengthy RF procedures that are common in clinical practice today.

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