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Microwave ablation versus radiofrequency ablation in the kidney: high-power triaxial antennas create larger ablation zones than similarly sized internally cooled electrodes

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Abstract

Purpose—To determine whether microwave ablation with high-power triaxial antennas creates significantly larger ablation zones than RF ablation using similarly sized internally cooled electrodes.

Methods—Twenty-eight 12-minute ablations were performed in an in vivo porcine kidney model. RF ablations were performed with a 200-W pulsed generator and either a single 17-gauge cooled electrode (n = 9) or three switched electrodes spaced 1.5 cm apart (n = 7). Microwave ablations were performed using one (n = 7), two (n = 3), or three (n = 2) 17-gauge triaxial antennas to deliver 90 W continuous power per antenna. Multiple antennas were powered simultaneously. Temperatures 1 cm from the applicator were measured during two RF and microwave ablations each. Animals were euthanized post-ablation and ablation zone diameter, cross-sectional area and circularity were measured. Comparisons between groups were performed using a mixed effects model with $P < .05$ indicating statistical significance.

Results—No adverse events occurred during the procedures. Three-electrode RF (mean area, 14.7 cm²) and single-antenna microwave (mean area, 10.9 cm²) ablation zones were significantly larger than single-electrode RF (mean area, 5.6 cm²; $P = .001$ and $P = .0355$, respectively). No significant differences were detected between single-antenna microwave and multiple-electrode RF. Ablation zone circularity was similar across groups ($P > .05$). Tissue temperatures were higher during microwave ablation (maximum temperature, 123 °C; versus 100 °C for RF).

Conclusion—Microwave ablation with high-power triaxial antennas created larger ablation zones in normal porcine kidneys than RF ablation with similarly sized applicators.

INTRODUCTION

Renal cell carcinoma (RCC) represents a significant clinical problem with approximately 33,000 new cases diagnosed each year in the United States (1). In addition to an underlying increase in the number of people developing RCC, a greater proportion of tumors are being detected while imaging for other indications (2,3). Nephron-sparing techniques, such as open or laparoscopic partial nephrectomy, cryoablation, and radiofrequency (RF) ablation,

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are increasingly being employed in an attempt to decrease morbidity and preserve renal function in patients with early RCC. These techniques are particularly useful for elderly or infirm patients, or those with multiple-tumor syndromes (e.g. von Hippel-Lindau), significant co-morbidities, compromised renal function, or a prior nephrectomy.

Early reports of RF ablation for RCC have been promising in terms of safety and efficacy (4,5). RF is effective for small (< 3 cm) and exophytic tumors; however, the technical failure rate increases for larger or more centrally located tumors (5,6). This is likely due to a desire to avoid injuring the renal pelvis and ureters as well as perfusion-mediated cooling from large central renal vessels. This effect may be particularly detrimental during RF ablation of the kidney since the perfusion rates of both kidney tumors and the surrounding normal parenchyma, especially near the hilum, are higher than those of liver tissue for tumors for which RF ablation is more typically used (7,8). Therefore, there is a need for more effective ablation systems that coagulate large volumes of tissue in a highly vascular environment like normal renal parenchyma and renal tumors.

Tissue perfusion and vascular mediated cooling has less of an impact on microwave ablation when compared with radiofrequency ablation. RF ablation is more dependent on thermal conduction due to lower tissue temperatures and longer treatment times (9). Yu et al (10) found that hepatic veins had minimal effect on microwave ablation zones, and Wright et al (11) found that microwave ablation was less susceptible to the “heat sink” effect of local blood flow when directly compared with RF. Given that microwave ablation is less susceptible to perfusion-mediated cooling than RF, microwave ablation is theoretically better suited to heating kidney tissue. Brace et al (12–14) have demonstrated the ability to create large zones of necrosis in both ex vivo and in vivo liver models using a single small-diameter (17-gauge) resonant monopole antenna (ie, a triaxial antenna) operated at high powers (>50 Watts). The purpose of this study was to determine whether microwave ablation with high-power triaxial antennas creates significantly larger zones of ablation in an in vivo porcine kidney model compared to RF ablation with internally cooled electrodes.

MATERIALS AND METHODS

This manuscript was written in accordance with the standardized terminology and reporting criteria for thermal ablation (15).

Animals, Anesthesia and Procedures

The study was approved by the research animal care and use committee of our institution, and all husbandry and experimental studies were compliant with the National Research Council's *Guide for the Care and Use of Laboratory Animals* (16). Twenty-eight ablations were performed in 14 female domestic pigs (mean weight, 69 kg). Preanesthetic sedation was induced with intramuscularly administered tiletamine hydrochloride–zolazepam hydrochloride (7 mg per kilogram of body weight, Telazol; Fort Dodge Laboratories, Fort Dodge, Iowa) and 2.2 mg/kg xylazine hydrochloride (Xyla-Ject; Phoenix Pharmaceutical, St Joseph, Mo). Atropine (0.05 mg/kg; Phoenix Pharmaceutical) was administered to facilitate intubation. The animals were intubated, and anesthesia was induced and maintained with inhaled 2% isoflurane (Halocarbon Laboratories, River Edge, NJ). A midline incision was used to expose the kidneys, which were left in place behind an intact peritoneum. Each animal received two ablations, one per kidney. Applicators were placed perpendicular to the anterior aspect of the kidney and centered in the lower pole to a depth such that the active heating volume was centered in the kidney. Ablations were performed for 12 minutes in each group as described in Experimental Groups below. Fiberoptic thermosensors (Luxtron; Santa Clara, CA) were used to measure tissue temperatures 1 cm from the applicator during two trials each of single-electrode RF and single-antenna microwave ablation. Sensors were

inserted to the same depth as the base of the microwave antenna (the level of the electric field peak) or the middle of the active RF electrode. The animals were monitored during the procedures for any signs of complications. After both ablations were performed, the animals were euthanized with an intravenous overdose of pentobarbital sodium and phenytoin sodium (Beuthanasia-D; Schering-Plough, Kenilworth, NJ), and the kidneys were removed en bloc.

Experimental Groups

Groups 1 and 2 consisted of RF ablations performed using the Cool-tip RF ablation system (Valleylab, Boulder, CO). Ablations in Group 1 ($n = 9$) were created using a single 17-gauge electrode with a 3-cm active tip. Group 2 ($n = 7$) consisted of multiple-electrode ablations performed with three single electrodes spaced 1.5 cm apart. Groups 3–5 consisted of microwave ablations performed using 17-gauge triaxial antennas. Microwave ablations were performed with one, two, and three antennas for Group 3 ($n = 7$), Group 4 ($n = 3$) and Group 5 ($n = 2$), respectively. Fewer samples were collected in the multiple-antenna microwave groups because kidney size was insufficient to permit full ablation in most cases.

Microwave and RF Ablations

The RF ablation system has been described previously (17,18). Briefly, the system utilizes a 200-W radiofrequency generator operating at 480 kHz, and employs an impedance feedback loop, pulsed energy delivery and straight internally cooled electrodes. When used to power a single electrode (Group 1), the generator temporarily reduces the output power if the impedance rises 10 Ω above baseline. The multiple-electrode system (Switching Controller, Covidien) used for Group 2 switches between two or three electrically independent electrodes when tissue impedance rises 30 Ω above baseline or after a time interval of 30 seconds.

Microwave ablations were performed using high-power 17-gauge triaxial antennas. The triaxial design minimizes reflected power to maximize energy deposition without increasing antenna diameter substantially and has been characterized in liver and lung tissue models (13,14,19). A 2.45 GHz generator (Coher-Muegge, LLC, Norwalk, CT) supplied 90 W to each antenna. In multiple-antenna ablations, power was distributed using a two- or three-way splitter (SM Electronics, Fairview, TX). An acrylic spacer was used during multiple-applicator ablations to ensure accurate electrode spacing and parallel electrode insertion.

Ablation Zone Measurements

Zones of ablation were excised, sliced into approximately 4-mm sections and measured for size and shape. A representative slice was selected from the middle of each ablation zone and stained with 2,3,5-Triphenyl-2H-tetrazolium chloride (TTC, a stain for mitochondrial activity in viable tissue) to better demarcate the zone of complete necrosis. Ablation zone slices were optically scanned (Perfection 2450 Photo Model G860A; Epson, Long Beach, CA) and saved as electronic images. Ablation zone minimum and maximum diameter, area, and circularity were measured on the TTC-stained slice using the freeware ImageJ (NIH, Bethesda, MD). Measurements only included the zone of complete necrosis, as delineated by the TTC stain. Mean diameters were calculated as the average of the minimum and maximum diameters. Circularity is a measure of the “roundness” of an ablation, and was measured directly using ImageJ. A perfect circle has a circularity of 1.0.

Statistical Analysis

A mixed model with animals modeled as random effects was used to test for differences in ablation zone size and shape among single-electrode RF, multiple-electrode RF, and single-

antenna microwave by using software (SAS, version 8.0; SAS Institute, Cary, NC). A *P* value less than .05 was considered to indicate a significant difference. Two- and three-antenna microwave ablation zones were not included in the formal statistical analysis because of the small number of samples in these groups.

RESULTS

All animals tolerated the procedures well and no complications were encountered.

Ablation zone sizes and shapes are listed in Table 1. Figure 1 compares the mean ablation zone diameters between groups. Figure 2 shows representative slices of ablation zones created in each of the groups. Multiple-antenna microwave ablation created the largest ablation zones, followed by multiple-electrode RF, single-antenna microwave and single-electrode RF. Ablation zones created using multiple-electrode RF (mean area, 14.7 cm²) and single-antenna microwave (mean area, 10.9 cm²) configurations were significantly larger when compared with those created using a single RF electrode (mean area, 5.6 cm²; *P* = .0010 and *P* = .0355 for multiple-electrode RF and single-antenna microwave vs single-electrode RF, respectively). Mean minimum and maximum diameter of ablation zones created using single-antenna microwave and multiple-electrode RF were also significantly larger than those created with single-electrode RF. No significant differences in ablation zone size were detected between single-antenna microwave and multiple-electrode RF. The mean circularity of coagulation zones was similar among groups included in the analysis (single-electrode RF, 0.88 ± 0.06; single-antenna microwave, 0.90 ± 0.04; multiple-electrode RF, 0.84 ± 0.07; *P* > .05, all comparisons). The mean circularity of the three-antenna microwave ablation group was the lowest because the size of the kidneys limited ablation zones in this group the most, creating non-circular ablation zones that followed the borders of the kidney. Figure 3 shows the temperature curves during the RF and microwave ablations. Microwave energy heated tissue faster than RF and higher tissue temperatures were observed during microwave ablation (mean maximum temperature, 123 °C; compared to 100 °C for RF ablation).

DISCUSSION

This study demonstrates that microwave ablation with high-power triaxial antennas may be used to create larger zones of ablation than RF in an in vivo porcine kidney model. For a given number of applicators, ablations with triaxial antennas were significantly larger than RF ablations. In addition, ablation zones created using one or two triaxial antennas were comparable to those created using three RF electrodes. In other words, a given volume of tissue can be coagulated with fewer microwave antennas than RF electrodes. The faster heating and higher tissue temperatures achieved with microwaves is considered to be an important advantage when compared with RF ablation.

The superior performance of microwave ablation compared with RF ablation in the kidney may be attributed to the different mechanisms of heating of the two modalities. RF ablation is based on resistive heating caused by electrical current, which only dominates within approximately 1 cm of the electrode. Tissue further away from the electrode is heated via thermal conduction, making it more susceptible to perfusion-mediated cooling. In addition, treatment temperatures must be kept under 100 °C to prevent charring and impedance increases which limit RF energy deposition. On the other hand, microwave ablation is based on dielectric heating, and active tissue heating dominates in tissue up to 2 cm away from the antenna. Microwaves can also heat tissue an order of magnitude faster than RF and are not hindered by charring. Therefore, temperatures can be driven considerably higher, which creates a larger thermal gradient and increases thermal conduction. Given the high water

content and perfusion rate of kidneys, microwave ablation may actually be more effective in the kidney when compared with other less hydrated organs such as the liver.

The triaxial microwave ablation system utilizes a resonant design to limit reflected power, thereby enabling higher input powers and maximizing energy deposition in tissue. Importantly, the design does not increase the physical dimensions above that of the single RF electrode (17-gauge). Therefore, the triaxial system can be used to increase the volume of tissue coagulated without increasing the invasiveness of the procedure. Also, arrays of triaxial antennas can be safely applied to further increase the volume of coagulation, as demonstrated in this study and previous studies in liver and lung (13,19). Several multiple-antenna ablations were performed in this study, but were excluded from the statistical analysis because fewer samples were collected given that the size of the kidneys severely limited the growth of the ablation zones. Two- or three-antenna configurations allowed ablation of a significant portion of the kidneys and should be reserved for larger tumors given the possibility of greater complications with larger ablation zones if inappropriately applied.

Hope et al recently characterized the performance of a 915 MHz microwave ablation system in an in vivo porcine kidney model (20). They established an optimal time (10 min) and power (45 W) combination, which resulted in ablation zones with a mean diameter of 2.0 cm. Longer ablation times (20 min) and larger powers (60 W) did not significantly increase the size of the ablation zone. In contrast, our study found that applying 90 W for 12 min resulted in much larger ablation zones (mean diameter, 3.6 cm). The power delivered to the tissue is a function of the generator output power, the losses within the coaxial cables feeding the power from the generator to the antenna, and the antenna design. As indicated above, the triaxial antenna used in our study was designed to minimize power reflected at the antenna-tissue interface, which maximizes the amount of input power deposited in tissue. In addition to increasing power delivered to the tissue, minimizing reflected power also enables the use of smaller antennas that are safer for percutaneous use—the triaxial antenna is 17 gauge compared to the 13-gauge antenna used by Hope et al.

Clinical experience with microwave ablation for kidney tumors is limited, but early results are promising. Clark et al performed microwave ablations in ten patients who subsequently underwent a nephrectomy (21). They reported mean ablation zone dimensions of $4.1 \times 2.7 \times 2.2$ cm using a 13-gauge antenna and a generator output of 60 W. In addition, histological analysis demonstrated uniform cell death within the ablation zone. Liang et al recently reported the results of a feasibility study in which they performed ultrasound-guided microwave ablation on 12 patients with renal cell carcinoma (22). Complete tumor necrosis was achieved in all cases and no residual or recurrent tumor was detected at a median follow-up of 11 months.

A known complication of renal RF ablation is injury to the collecting system leading to obliteration of calyces or ureteral strictures (23). While the underlying mechanism of injury is likely to be largely thermal, there may also be an electrical component given the electrolytic content of urine and the physics of RF ablation (ie, electrical current flowing through electrolytic tissue). Given that microwave ablation does not rely on electrical current flow, it may decrease the risk of damage to the collecting system during renal ablation. Further studies are needed to characterize the underlying mechanism of calyceal injury and to determine whether one modality is safer than the other.

The most significant limitation of this study was the use of an open surgical approach in a normal porcine kidney model. At the time of the study, a large animal kidney tumor model was not available. The highly vascular nature of renal cell carcinoma makes it likely that the

results will translate to tumors. However, additional studies are still needed to optimize the performance of the microwave system in tumor models. Given the heterogeneous makeup of the kidney, the effects of antenna placement on coagulation size and shape also need to be investigated. Finally, fewer samples were collected in the multiple-antenna microwave groups because the small size of the kidneys severely limited the growth of the ablation zone. Further work characterizing the performance of multiple-antenna configurations is warranted.

In conclusion, microwave ablation with triaxial antennas created larger zones of ablation in normal porcine kidneys than RF ablation, and offers the potential to increase the effectiveness of tumor ablation for treating larger renal tumors. Microwave ablation may also reduce the invasiveness and complication rate associated with thermal ablation of kidney tumors by decreasing the size and number of applicators needed to achieve a given volume of coagulation.

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Figure 1.

Graph depicts mean ablation zone diameters. Single-antenna microwave and multiple-electrode RF ablations were significantly greater than single-electrode RF ablations. No significant differences were detected between single-antenna microwave and multiple-electrode RF ablations. Statistical comparisons were not made between the multiple-antenna groups and the others because the size of the kidneys limited the growth of the multiple-antenna ablations.

2a

2b

2c

2d

2e

Figure 2.

Representative slices of ablation zones created using single-electrode RF (A), multiple-electrode RF (B), single-antenna microwave (C), two-antenna microwave (D), and three-antenna microwave (E) configurations. A–C, Ablation zones were skewed toward the periphery of the kidney because temperatures $> 50^{\circ}\text{C}$ coagulate blood vessels and decrease perfusion in regions of tissue downstream. D–E, The growth of multiple-antenna ablation zones was significantly limited by the size of the kidneys. Slices were stained with TTC, a marker for mitochondrial enzyme activity, to better demarcate viable (purple) from necrotic (pale) tissue. Note—Lengths of bars are 1 cm. Arrows indicate margins of ablation zones.

Figure 3.

Graph shows mean temperatures recorded 1 cm from the applicator during two RF and two microwave ablations. RF ablation is limited to temperatures < 100 °C because higher temperatures lead to tissue desiccation, charring, and subsequent increases in electrical impedance. The oscillations in the RF temperature curve are due to a built-in power pulsing algorithm. Note the faster, continuous tissue heating and higher maximum tissue temperatures associated with microwave ablation.

Table 1

Ablation Zone Measurements

Group	N	Minimum Diameter (cm)	Maximum Diameter (cm)	Area (cm ²)	Circularity
RF ablation					
Single-electrode	9	2.1 ± 0.3 ^{*,†}	2.9 ± 0.3 ^{§,}	5.6 ± 1.0 ^{#,**}	0.88 ± 0.06
Three-electrode	7	3.9 ± 0.7 [‡]	4.5 ± 0.4 [¶]	14.7 ± 3.7 ^{††}	0.84 ± 0.07
Microwave ablation					
Single-antenna	7	3.2 ± 0.8	3.9 ± 1.0	10.9 ± 6.2	0.90 ± 0.04
Two-antenna	3	3.9 ± 0.7	5.8 ± 0.6	14.1 ± 3.4	0.86 ± 0.10
Three-antenna	2	3.8 ± 0.5	6.9 ± 0.5	22.8 ± 1.1	0.73 ± 0.04
P value	-	0.0005	0.0010	0.0037	0.2330

Note—Multiple-antenna microwave ablations were not included in the statistical analysis because the ablation zones were larger than the renal pole in which they were placed.

* P = .0001 versus three-electrode RF

[†] P = .0087 versus single-antenna microwave

[‡] P = .0977 versus single-antenna microwave

[§] P = .0003 versus three-electrode RF

^{||} P = .0105 versus single-antenna microwave

[¶] P = .1139 versus single-antenna microwave

[#] P = .0010 versus three-electrode RF

^{**} P = .0355 versus single-antenna microwave

^{††} P = .0794 versus single-antenna microwave