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Creation of short microwave ablation zones: In Vivo Characterization of single and paired Modified Triaxial Antennas Laboratory Investigation

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Abstract

Purpose—To characterize modified triaxial microwave antennas configured to produce short ablation zones.

Materials and Methods—50 single- and 27 paired-antenna hepatic ablations were performed in domestic swine (n=11) with 17-gauge, gas-cooled modified triaxial antennas powered at 65W from a 2.45 GHz generator. Single-antenna ablations were performed at 2 (n=16), 5 (n=21), and 10 (n=13) minutes. Paired-antenna ablations were performed at 1-cm and 2-cm spacing for 5 (n=7, n=8) and 10 minutes (n=7, n=5). Mean transverse width, length and aspect ratio of sectioned ablation zones were measured and compared.

Results—For single antennas, mean ablation zone length was 2.9±0.45, 3.5±0.55 and 4.2±0.40 cm at 2, 5, and 10 minutes respectively. Mean width was 1.8±0.3, 2.0±0.32, 2.5±0.25 cm at 2, 5, and 10 minutes. For paired antennas, mean length at 5 min 1 and 2 cm and 10 min 1 and 2 cm spacing was 4.2±0.9, 4.4±0.9, 4.8±0.5 and 4.3±0.9 cm respectively. Mean width was 3.1±1.0, 4.0±0.8 and 3.8±0.4, 4.2±0.6 cm respectively. Paired-antenna ablations were more spherical (aspect ratios 0.72-0.79 for 5-10 min) than single-antenna ablations (0.57-0.59). For paired-

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antenna ablations, 1 cm spacing appeared optimal, with improved circularity and decreased clefting compared to 2 cm spacing (circ 1 cm 0.85, 2 cm 0.78).

Conclusion—Modified triaxial antennas can generate relatively short, spherical ablation zones. Paired-antenna ablations were rounder and larger in transverse dimension compared to single antenna ablations, with 1 cm spacing optimal for confluence of the ablation zone.

Introduction

Although radiofrequency ablation has been the most commonly used and researched heat based modality to date, microwave ablation is gaining increased adoption due to a variety of advantages. These include more rapid generation of hotter temperatures, larger ablation zones when using high power, decreased susceptibility to heat sinks, and improved energy penetration in lung, bone and charred/dessicated tissue (1-6). Despite these advantages, a substantial limitation to using microwaves is the length of the ablation zone, which is often substantially greater than the transverse dimension and can be upwards of 6-8 cm when using a single antenna (7-10). These larger, longer, hotter ablations could have increased potential to cause damage to adjacent vulnerable structures or burns to the body wall if not carefully monitored. Further, many tumors are somewhat spherical and longer ablation zones may lead to increased treatment of normal background organs proximal and distal to the mass. To date, *in vivo* reports of microwave ablation have focused on increasing the transverse diameter of the ablation zone, often at the cost of increased length (7-10).

Ablation zone length is impacted by many factors, including antenna design and radiating segment, frequency/wavelength, ablation time, and applied power(11-14). A dual slot antenna design has shown promise in producing a shorter, more spherical ablation zone, but is not yet commercially available (15, 16). Several vendors may be working on an antenna to generate shorter ablation zones. A gas-cooled modified triaxial antenna has recently become commercially available which has been designed to produce shorter, tip-weighted ablation zones. The purpose of this study was to test and characterize both single and paired modified triaxial antennas in an *in vivo* swine model.

Materials and Methods

Animals, Anesthesia and Overview of Procedures

Approval for this study was obtained from the institutional research animal care and use committee, and all husbandry and experimental studies were compliant with the National Research Council (see http://www.nap.edu/catalog/php?record_id=12910). Eleven female domestic swine (Arlington Farms, Arlington, Wis) were used for this study. Preanesthetic sedation was achieved with ketamine. Sedated animals were intubated, and anesthesia was maintained with inhaled isoflurane (Halocarbon Laboratories, River Edge, NJ). The liver was surgically exposed at laparotomy with a bilateral subcostal incision to enable applicator placement and to verify proper positioning. Microwave ablation was then performed in each of four distinct liver lobes, and different ablation times were distributed among the animals to reduce sampling bias. Following the ablation procedures (which took approximately 2-3 hours), animals were euthanized with an overdose of pentobarbital sodium and phenytoin

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sodium (Beuthanasia-D; Schering-Plough, Kenilworth, NJ). Zones of ablation were immediately excised and sectioned as described below.

Microwave Ablations

All microwave ablations were performed from an open approach using 17-gauge gas-cooled modified triaxial antennas with a 15 mm radiating segment (Precision, PR 15, NeuWave Medical, Madison WI). Microwave power was applied continuously at 65 W from the 2.45-GHz solid state generator. A total of 50 single-antenna ablations were performed for 2 (n=16), 5 (n=21), and 10 minutes (n=13). These time periods were selected based on prior *in vivo* work and clinical experience with a conventional triaxial antenna (10). At least one ablation was performed in each lobe of each porcine liver. A total of 27 paired-antenna ablations were also performed in a similar fashion, with the antennas spaced 1 or 2 cm apart and both powered at 65 W for 5 (n=7, n=8) and 10 minutes (n=7, n=5) respectively. These times and spacings were also based on prior in vivo/ex vivo work and clinical experience (17-19).

Measurements of Ablation Zone Size and Shape

Ablation zones were excised en bloc and were sectioned parallel to the ablation applicator to optimize length measurements (coronal to the applicators for the paired antennas). Samples were optically scanned (Perfection 2450 Photograph, model G860A; Epson, Long Beach, Calif) and saved as electronic images. Standard ablation zone metrics including length, transverse dimension, area, and aspect ratio (width:length) were analyzed using free software (ImageJ; 1.45s, National Institutes of Health, Bethesda, MD)(20). Circularity was measured for the paired-antenna ablations.

Statistical Analysis

Descriptive statistics of each metric (mean length, transverse dimension, area, aspect ratio) were calculated at each time point for both single and paired MW ablations, and are reported as mean ± 1 SD (standard deviation). Volumes were also calculated using the formula for the volume of an ellipsoid ($4/3 \prod abc$). The single antenna modified triaxial data was compared across time points using a Wilcoxon rank sum test. The paired antenna data was compared by time within spacing and then by spacing within time using a Wilcoxon rank sum test. Length and area of paired antenna ablation zones were also compared to single antenna ablations performed at the same time and power using Kruskal-Wallis tests with Wilcoxon rank sum test used for the two comparisons of each of the two-antenna ablations against the single antenna. The analysis did not account for clustering of lobes within animals because lobes were considered as independent. Exploratory and diagnostic plots were obtained to assess the validity of statistical test assumptions. A *P*-value less than 0.05 was considered to indicate a significant difference. There was no adjustment of p-values for multiplicity. Statistical analyses were performed in R2.15.2 (R Development Core Team 2012)(21).

Results

The mean ablation zone lengths for single-antenna ablations at 2 min, 5 min and 10 min (65 W) were 2.9±0.45, 3.5±0.55 and 4.2±0.4 cm respectively (figure 1). These ablation zones had corresponding transverse dimensions of 1.8±0.27, 2.0±0.32, and 2.5±0.25 cm, respectively. Aspect ratios for all single antenna ablations were approximately 0.6 (table 1, figure 1). There was significant growth in both length and area between 2 and 5 minutes ($p=0.001$, $p=0.01$) with continued significant growth from 5 to 10 minutes ($p=0.0009$, $p<0.0001$).

The paired antenna ablations showed lengths of 4.2±0.9 and 4.9±1.0 cm for 5 minute ablations (65W each antenna) at 1 cm and 2 cm spacing, respectively. Lengths of 4.8±0.5 and 4.8±1.3 cm were seen at 10 minutes, 1 and 2 cm spacing. Transverse dimensions were 3.1±1.0 and 4.4±0.7 at 5 minutes, 1 and 2 cm spacing respectively. Transverse dimensions were 3.8 ±0.4 and 4.5±0.7 cm at 10 minutes, 1 and 2 cm spacing respectively. Paired-antenna ablations were more spherical than single-antenna ablations, with aspect ratios greater than 0.7 (figure 2, table 2). There was a prominent trend toward significant growth in the transverse dimension and area between 5 and 10 minutes at 1 cm spacing ($p=0.07$, $p=0.053$). There was a statistically significant increase in length between 5 and 10 minutes at 1 cm spacing ($p=0.05$). There was no significant difference in length, transverse diameter or area between 5 and 10 minutes at 2 cm spacing. At an ablation time of 5 minutes, there was no significant difference in length between 1 and 2 cm spacing ($p=0.2$), but there was a significant difference in transverse dimension ($p=0.02$) and in area ($p=0.04$). At an ablation time of 10 minutes, there was no statistically significant difference in length, transverse dimension or area at a spacing of 1 vs 2 cm. There was a trend toward significance in transverse diameter at 2 cm spacing ($p=0.1$). However, qualitatively, ablation zones performed at the 2 cm spacing would often develop a bilobed appearance (figure 3). In addition, overall, ablations performed at 1 cm spacing showed slightly improved circularity (0.85) compared to ablations performed at 2 cm spacing (0.78). Calculated volumes showed similar trends.

When comparing single to paired antenna ablations, there was a significant increase in transverse dimension and area at the 5 minute time point for the both the 1 and 2 cm spacings. Although there was a significant increase in length at the 2 cm spacing ($p=0.002$), this did not meet statistical significance for the 1 cm spacing ($p=0.06$). There was a significant increase in area and transverse dimension when comparing single to paired antenna at the 10 minute time point for both spacings, but no significant increase in length at the 2 cm spacing (table 3).

Discussion

Microwaves have many theoretical advantages as a heat based ablation modality, but one of the limitations has been the length of the ablation zone generated. In this study, we began to characterize a modified triaxial antenna created to generate short ablations zones in an *in vivo* porcine model. Although single antennas create relatively elliptical ablations, the length was around 4 cm, despite continued growth of the transverse dimension over time. Paired antennas created more spherical ablations, with increased transverse dimension compared to single antenna ablations, but with slightly less prominent increases in length. One-cm spacing appeared optimal due to increased clefting and decreased circularity seen at 2-cm spacing (figures 2, 3).

Multiple series have reported microwave ablation zone lengths greater than 5 cm (table 4) or qualitatively described elongated, somewhat cylindrical, rather than round ablation zones (7-10). To date, there has been limited commercial availability of a microwave antenna capable of generating short ablation zones similar to those seen with radiofrequency ablation but still capturing the other potential advantages of microwave ablation. The results of this study show that a modified triaxial antenna is able to generate shorter ablation zones than those described in the literature using other antenna designs.

When compared to data acquired in a similar *in vivo* model using a single conventional triaxial antenna, the single modified triaxial antenna showed shorter ablation zone lengths (3.5-4.2 cm for the modified triaxial and 5.3-5.8 cm for the conventional triaxial antenna at 5-10 min). It is important to keep in mind that the conventional triaxial antenna was powered in vivo at 140 W compared to 65 W on the modified triaxial antenna, which could also impact the length.

However, long ablation zones can be seen even at lower powers (Table 4), suggesting that this effect is not due to differences in power alone. In fact, single-antenna microwave ablations performed with a modified triaxial antenna were comparable in length to, but more spherical than, RF ablation zones generated under similar conditions (10). Similarly, Mulier et al performed a large literature search evaluating the reported size and geometry of hepatic radiofrequency lesions. There was a relative paucity of length data, but in *in vivo* porcine models, lengths ranging from 2-4.4 cm were reported with a variety of devices including straight water cooled needles and umbrella or deployable devices (22). In HCC and metastatic lesions, very little length data is reported but one study treating metastatic lesions reports lengths of 3.4 cm±0.3 using a 3 cm active zone water cooled straight needle (23). The lengths seen with this modified triaxial antenna are similar.

The single-antenna ablations showed significant growth from 2 to 5 minutes, and from 5 to 10 minutes, unlike RF ablations performed under similar conditions, which showed little growth between 5 and 10 minutes (10). This is most likely due to differences in mechanism of heating (volume heating with dielectric hysteresis vs conduction of current through increasingly charred, dessicated tissue).

Not surprisingly, paired modified triaxial antennas generated larger ablation zones than a single antenna. Notably, this growth is seen more in the transverse dimension with less prominent increases in length, so that paired-antenna ablation zones remained round. There was also growth in size of the ablation zone between 5 and 10 minutes, with increases seen in transverse dimension, area, volume and length. One would expect larger ablation zones with longer time periods, but this may be complicated by the possibility of increased tissue contraction for longer ablation times, which may decrease the final ablation zone size (24).

Although larger ablation zones, particularly in transverse dimension and area, were seen at 2 cm spacing compared to 1 cm, the differences seemed largely due to the additional separation and were not statistically significant at the 10 minute time point. In fact, since the difference in the mean transverse dimension of the ablation zone was 7 mm at 10 min, less than the additional 10 mm separation between antennas, it seems possible that the added separation actually decreased the thermal synergy between the antennas. Indeed, many of the ablations created with a 2 cm separation were qualitatively more clefted or bilobed in appearance and were less circular, which has also been seen with the clinical application of this antenna (figure 4). This data would suggest that 1 cm spacing is preferred.

This antenna has been very promising in early clinical use, generating round, tip-weighted ablation zones as described in the *in vivo* model (figure 5). This shorter, tip-weighted ablation zone creates additional flexibility in the application of microwave technology and may expand microwave applications. For large tumors or metastatic disease, where a large ablation zone is needed, a more conventional antenna design can be utilized. However, for small tumors adjacent to vulnerable structures, a modified antenna design such as a modified triaxial antenna could be used where in the past, a user might consider switching to a radiofrequency applicator. A small, short tip-weighted, round ablation zone could be used more readily in the retroperitoneum to treat renal tumors, to treat small osseous lesions such as osteoid osteomas or may be more practical for use in nerve ablation for chronic pain.

This study was limited by the exclusive use of normal porcine liver rather than a tumor model or cirrhotic liver. Recent data using a water-cooled 2.45 GHz system at 100 W (Amica, HS Medical, Boca Raton, FL) suggest that the expected performance in human tumors can be expected to lie somewhere between the performance seen in ex vivo and *in vivo* normal porcine livers (meeting abstract/unpublished data, Goldberg SN, Meloni F, Tosoratti N, Nissenbaum I, Appelbaum L, Solbiati L. World Conference on Interventional Oncology, 2011). Sectioning of the ablation zones directly parallel and coronal to the applicator can be challenging and may introduce some variability of measurements. The antennas were tested in single tissue type (liver), therefore translation into other tissues may require some additional study. All ablations were performed with a single microwave system and frequency.

This study has shown that short, tip-weighted ablation zones can be generated with single and paired modified triaxial microwave antennas. This has the potential to be an important tool in the ablation armamentarium, capturing the advantages of microwave without the length seen generated by many available systems. Continued exploration of other antenna designs may be helpful, to continue to optimize the shorter microwave ablation zone.

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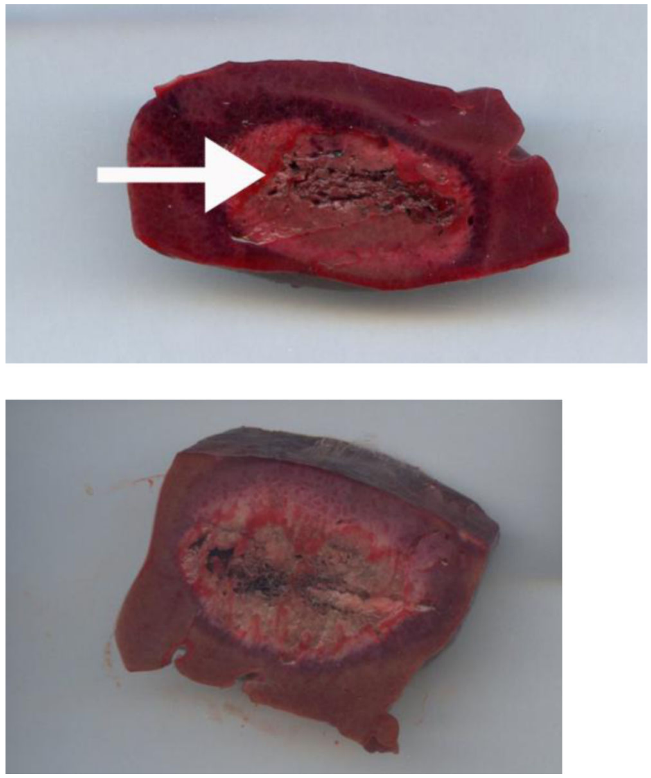

Figure 1.

Examples of scanned sectioned ablation zones performed with single microwave antennas at 2 min (a) and 5 min (b). These were sectioned parallel to the probe (see probe tract, arrow a) to optimize length measurements. Note the somewhat spherical ablation zones, particularly at 5 min (b).

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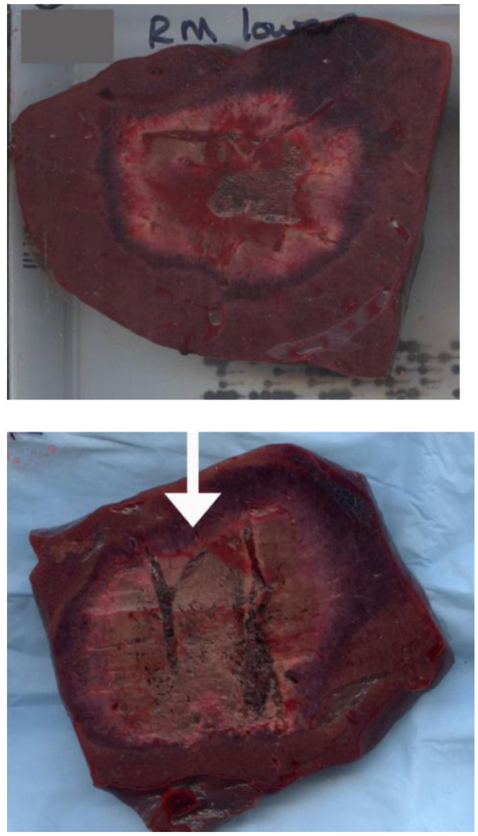

Figure 2.
Examples of scanned section paired antenna ablations, performed for 5 minutes at 1 cm (a) and 2 cm (b) spacing. The 2 cm spacing showed slightly larger ablation zones, but with occasional slight clefting (arrow, b) that was more prominent at 10 minutes.

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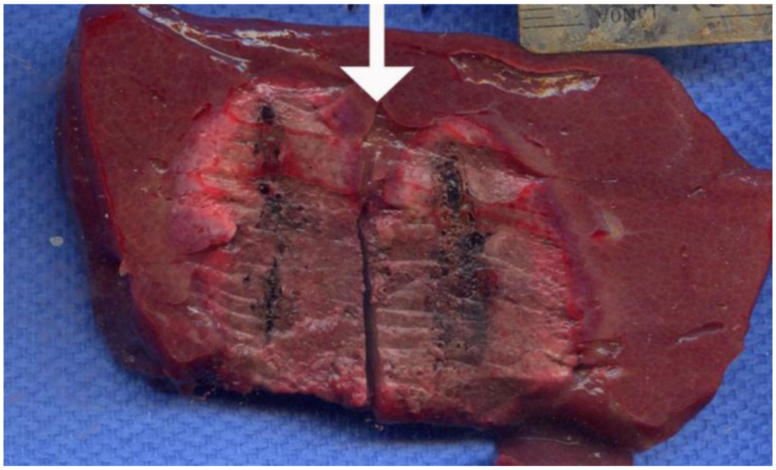


Figure 3.

Two antenna ablation performed for 10 minutes at 2 cm spacing. Note the slightly bilobed appearance or clefting at the top of the ablation zone (arrow). This was qualitatively noted on multiple ablation zones, suggesting that 1 cm spacing may be optimal.

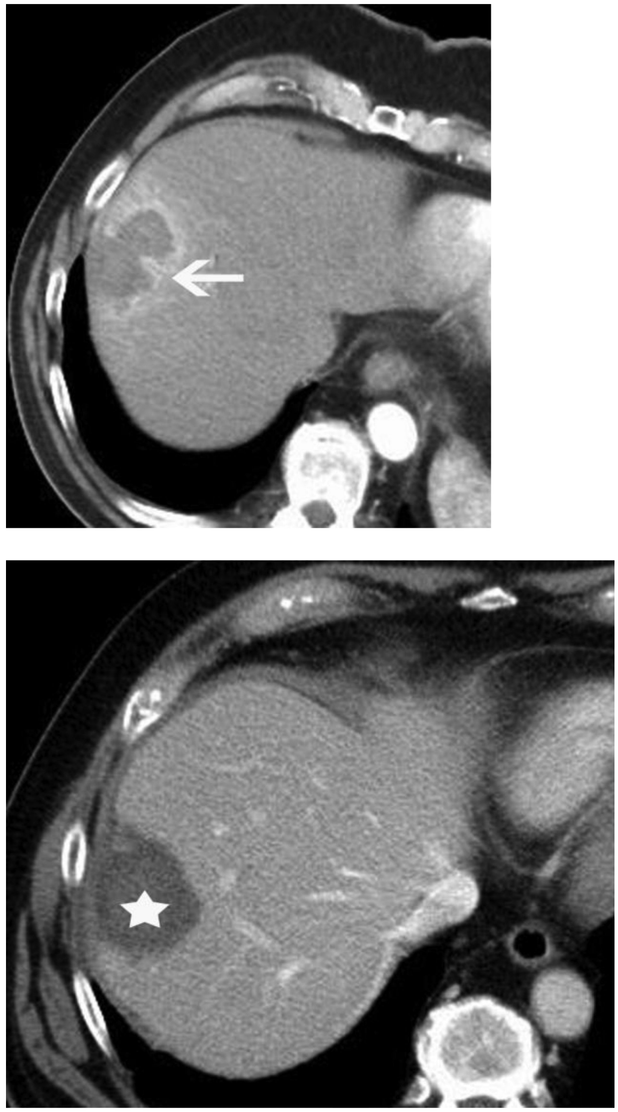
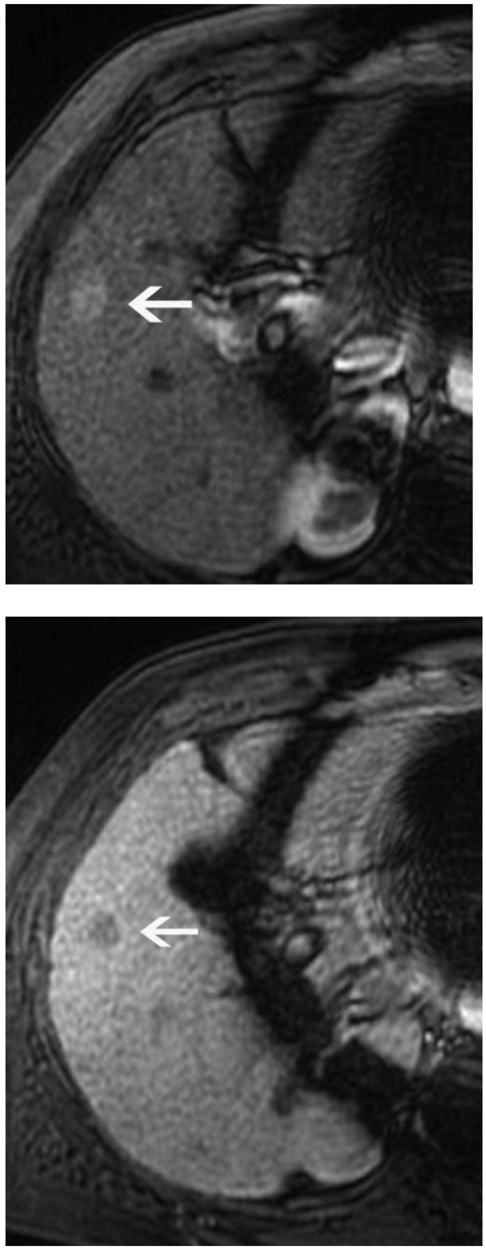


Figure 4.

Microwave ablation of a colorectal metastatic lesion. Preablation contrast enhanced CT image (a) demonstrates a small low attenuation lesion (arrow), representing metastatic colorectal cancer. Intraprocedural non contrast CT image (b) demonstrates two antennas spaced 2 cm apart (arrowheads). These were run for 7 minutes at 65 W and created the bilobed ablation seen on the post contrast post ablation CT image (arrow, c). The probes were repositioned approximately 1 cm apart and additional treatment was performed with production of a more rounded ablation zone (*, d).



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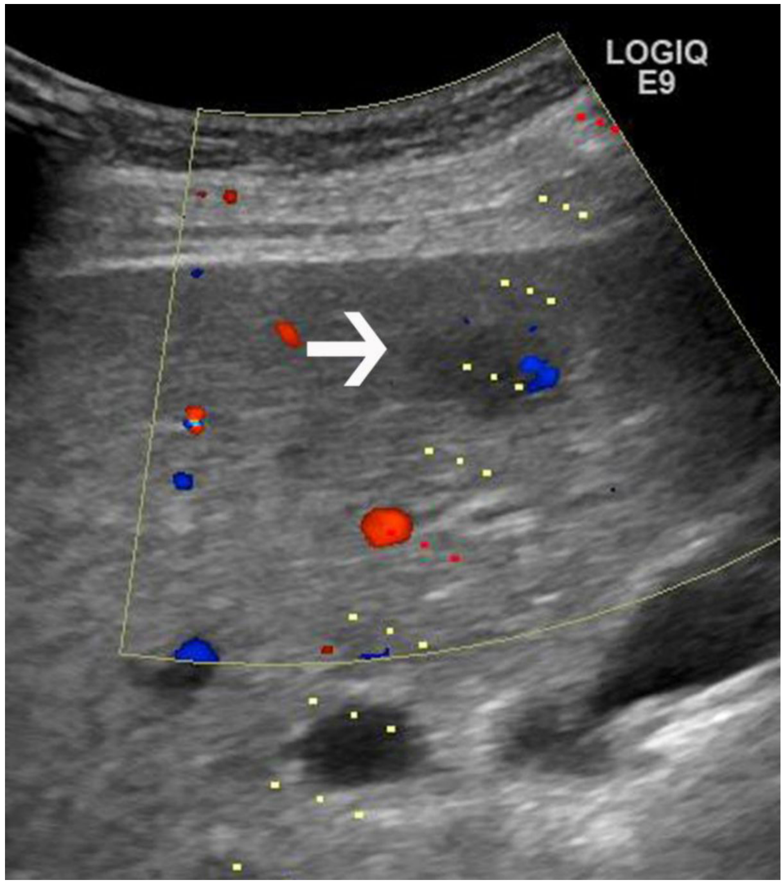

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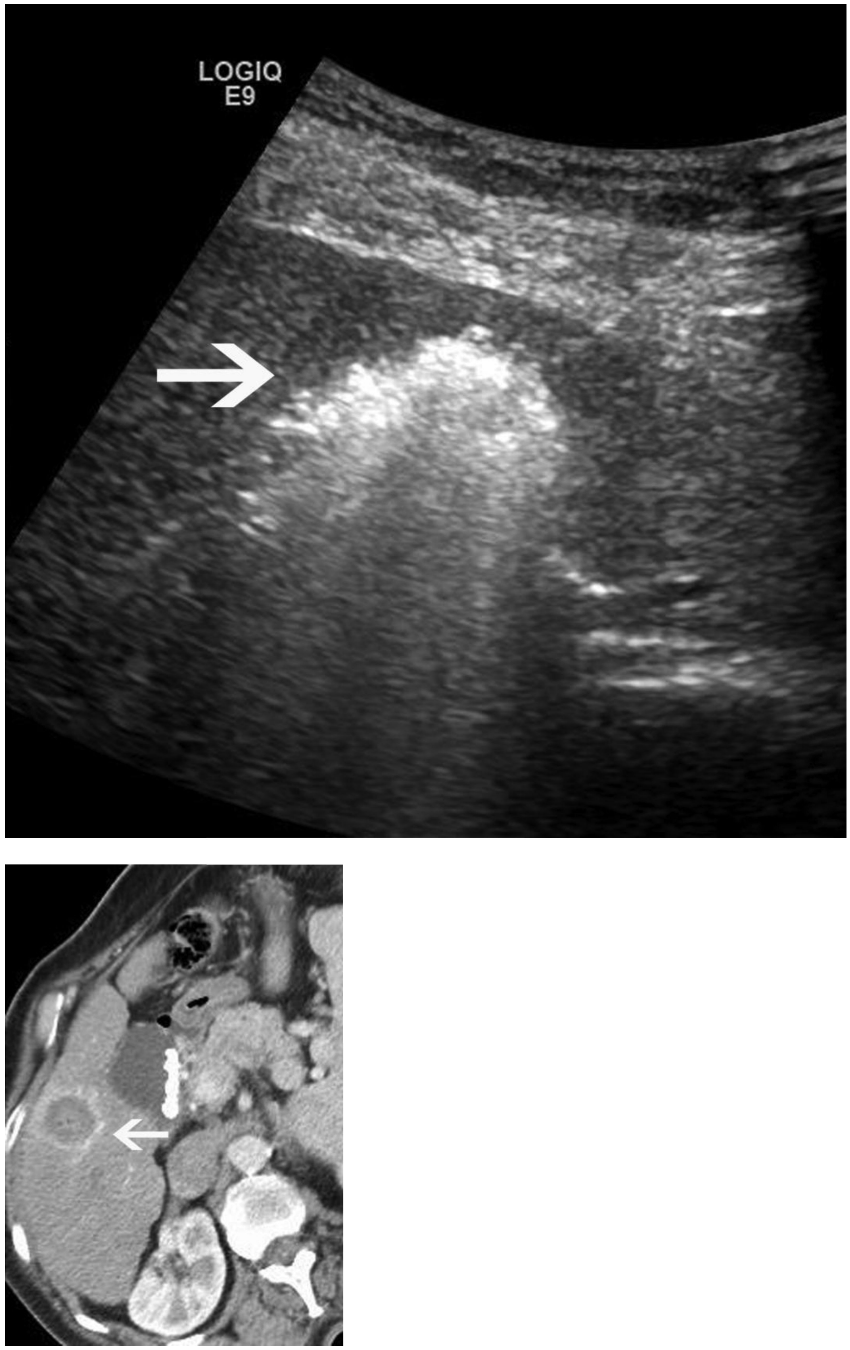

Figure 5.

Microwave ablation performed in a cirrhotic patient with an 18 x 15mm HCC. The preablation MRI demonstrates arterial enhancement (a) and washout (b) within the tumor (arrows), consistent with HCC. Intraprocedural US (c) redemonstrates the hypoechoic lesion (arrow), with the steam cloud encompassing the lesion in (d). A single antenna was run for 5 minutes at 65W, creating a spherical ablation zone measuring 2.8 × 2.8 cm, shown on axial post procedure contrast enhanced CT (arrow, e,).

Table 1

Single modified triaxial antenna microwave ablation dimensions

Time (min)	Length (cm)	Transverse dimension (cm)	Area (cm^2)	Volume (cm^3)	Aspect ratio (Trv:length)
2 (n=16)	2.9±0.45	1.8±0.27	3.9±1.0	4.9±1.9	0.61±0.09
5 (n=21)	3.5±0.55	2.0±0.32	5.3±1.4	7.4±2.9	0.57±0.13
10 (n=13)	4.2±0.4	2.5±0.25	8.1±1.5	14.2±3.3	0.59±0.07

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Table 2

Paired modified triaxial antenna microwave ablation dimensions

Time (min)	Spacing (cm)	Length (cm)	Transverse dimension (cm)	Area (cm^2)	Volume (cm^3)	Aspect ratio (Trv:length)
5	1	4.2±0.9	3.1±1.0	11.2±6.4	25.2±25	0.72±0.18
5	2	4.9±1.0	4.4±0.6	16.3±4.1	50.5±16	0.9±0.21
10	1	4.8±0.5	3.8±0.4	14.3±3.3	36.7±9.1	0.79±0.11
10	2	4.8±1.0	4.5±0.7	15.6±6.2	50.8±24	1.0±0.322

Table 3

Single vs Paired antenna microwave ablation dimensions

Number of antenna	Time (min)	Spacing (cm)	Length (cm)	Transverse dimension (cm)	Area (cm^2)	Volume (cm^3)	P-value (single vs paired)
Single	**5**	**n/a**	**3.5±0.55**	**2.0±0.3**	**5.3±1.4**	**7.4±2.9**	
Paired	**5**	**1**	**4.2±0.9**	**3.1±1.0**	**11.2±6.4**	**25.2±25**	**Length 0.06, trv dim 0.005, area <0.001**
Paired	**5**	**2**	**4.9±1.0**	**4.4±0.7**	**16.3±4.1**	**50.5±16**	**Length 0.002, trv dim <0.001, area <0.001**
Single	**10**	**n/a**	**4.2±0.4**	**2.5±0.3**	**8.1±1.5**	**14.2±3.3**	
Paired	**10**	**1**	**4.8±0.5**	**3.8±0.4**	**14.3±3.3**	**36.7±9.1**	**Length 0.02, area <0.001, trv dim <0.001**
Paired	**10**	**2**	**4.8±1.3**	**4.5±0.7**	**15.6±6.2**	**50.8±24**	**Length 0.6, area 0.002, 0.001**

Table 4

Selected *In vivo* Microwave Ablation zone dimensions

Study	System	Antenna Gauge	Diameter (cm)	Length (cm)
Wright et al, 2005(7)	**915 MHz, 40W, 10 min, H_2O cooling**	**13 g**	**Short axis 1.7±0.4, max diam 2.4±0.4**	**6.8±1.0**
Brace et al, 2007(21)	**2.45GHz, 68 W, H_2O cooling**	**14.5 g**	**2 min: 2.3 6 min: 2.6 12 min: 2.9**	**Not reported**
Awad et al, 2007(8)	**2.45 GHz, 100W, 2-8 min**	**>6 g**	**Mean short axis 2 min: 3.7±0.6 4 min: 3.8±0.5 8 min: 5.3±0.6**	**Mean long axis 2 min: 4.5±0.9 4 min: 4.9±0.5 8 min: 6.4±1.1**
Hines-Peralta et al, 2006(9)	**2.45 GHZ, 150W, 8 min**	**>6 g**	***In vivo* short axis 5.7 ±0.2**	**6.5±1.7**
Ianitti et al, 2007(28)	**915 MHz, 45 W, 10 min**	**14 g**	**1.59±3.5**	**Not reported**