ABSTRACT

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

**Materials and Methods:** Fifty single-antenna and 27 paired-antenna hepatic ablations were performed in domestic swine (N = 11) with 17-gauge gas-cooled modified triaxial antennas powered at 65 W 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 and n = 8, respectively) and 10 minutes (n = 7 and n = 5, respectively). Mean transverse width, length, and aspect ratio of sectioned ablation zones were measured and compared.

**Results:** For single antennas, mean ablation zone lengths were 2.9 cm ± 0.45, 3.5 cm ± 0.55, and 4.2 cm ± 0.40 at 2, 5, and 10 minutes, respectively. Mean widths were 1.8 cm ± 0.3, 2.0 cm ± 0.32, and 2.5 cm ± 0.25 at 2, 5, and 10 minutes, respectively. For paired antennas, mean length at 5 minutes with 1-cm and 2-cm spacing and 10 minutes with 1-cm and 2-cm spacing was 4.2 cm ± 0.9, 4.9 cm ± 1.0, 4.8 cm ± 0.5, and 4.8 cm ± 1.3, respectively. Mean width was 3.1 cm ± 1.0, 4.4 cm ± 0.7, 3.8 cm ± 0.4, and 4.5 cm ± 0.7, respectively. Paired-antenna ablations were more spherical (aspect ratios, 0.72–0.79) for 5–10 min) than single-antenna ablations (aspect ratios, 0.57–0.59). For paired-antenna ablations, 1-cm spacing appeared optimal, with improved circularity and decreased clefting compared with 2-cm spacing (circularity, 0.85 at 1 cm, 0.78 at 2 cm).

**Conclusions:** Modified triaxial antennas can generate relatively short, spherical ablation zones. Paired-antenna ablations were rounder and larger in transverse dimension than single antenna ablations, with 1-cm spacing optimal for confluence of the ablation zone.
has recently become commercially available which has been designed to produce shorter, tip-weighted ablation zones. The purpose of the present study was to test and characterize 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 (www.nap.edu/catalog.php?record_id=12910). Eleven female domestic swine (Arlington Farms, Arlington, Wisconsin) 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, New Jersey). 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. After the ablation procedures (which took approximately 2–3 h), animals were euthanized with an overdose of pentobarbital sodium and phenytoin sodium (Beuthanasia-D; Schering-Plough, Kenilworth, New Jersey). Zones of ablation were im mediately excised and sectioned as described later.

Microwave Ablations

All microwave ablations were performed from an open approach with the use of 17-gauge gas-cooled modified triaxial antennas with a 15-mm radiating segment (Precision PR 15; NeuWave Medical, Madison Wisconsin). 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 earlier 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 at 1 cm, n = 8 at 2 cm) and 10 minutes (n = 7 at 1 cm, n = 5 at 2 cm). These times and spacings were also based on earlier 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, California) and saved as electronic images. Standard ablation zone metrics including length, transverse dimension, area, and aspect ratio (width:length) were analyzed by using ImageJ software (version 1.45s; National Institutes of Health, Bethesda, Maryland) (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 single and paired microwave ablations, and are reported as mean ± one standard deviation. Volumes were also calculated by using the formula for the volume of an ellipsoid (4/3πabc). The single-antenna modified triaxial data were compared across time points by using a Wilcoxon rank-sum test. The paired antenna data were compared by time within spacing and then by spacing within time by using a Wilcoxon rank-sum test. Length and area of paired antenna ablation zones were also compared versus single antenna ablations performed at the same time and power by using Kruskal–Wallis tests, with a 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 .05 was considered to indicate a significant difference. There was no adjustment of P values for multiplicity. Statistical analyses were performed in R (version 2.15.2; R Foundation for Statistical Computing, Vienna, Austria) (21).

RESULTS

The mean ablation zone lengths for single-antenna ablations at 2 min, 5 min, and 10 min (65 W) were 2.9 cm ± 0.45, 3.5 cm ± 0.55 and 4.2 cm ± 0.4, respectively (Fig 1). These ablation zones had corresponding transverse dimensions of 1.8 cm ± 0.27, 2.0 cm ± 0.32, and 2.5 cm ± 0.25, respectively. Aspect ratios for all single-antenna ablations were approximately 0.6 (Fig 1, Table 1). There was significant growth in length (P = .001) and area (P = .01) between 2 and 5 minutes, with continued significant growth from 5 to 10 minutes (length, P = .0009; area, P < .0001).

The paired-antenna ablations showed lengths of 4.2 cm ± 0.9 and 4.9 cm ± 1.0 for 5-minute ablations (65 W each antenna) at 1-cm and 2-cm spacing, respectively. Lengths of 4.8 cm ± 0.5 and 4.8 cm ± 1.3 were seen at 10 minutes with 1-cm and 2-cm spacing, respectively. Transverse dimensions were 3.1 cm ± 1.0 and 4.4 cm ±
0.7 at 5 minutes with 1-cm and 2-cm spacing, respectively. Transverse dimensions were 3.8 cm ± 0.4 and 4.5 cm ± 0.7 at 10 minutes with 1-cm and 2-cm spacing, respectively. Paired-antenna ablations were more spherical than single-antenna ablations, with aspect ratios greater than 0.7 (Fig 2, Table 2). There was a prominent trend toward significant growth in the transverse dimension \((P = .07)\) and area \((P = .053)\) between 5 and 10 minutes at 1-cm spacing. There was a statistically significant increase in length between 5 and 10 minutes \((P = .05)\). There were no significant differences 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-cm and 2-cm spacing \((P = .2)\), but there was a significant difference in transverse dimension \((P = .02)\) and in area \((P = .04)\). At an ablation time of 10 minutes, there was no statistically significant difference in length, transverse dimension, or area at a spacing of 1 cm versus 2 cm. There was a trend toward significance in transverse diameter at 2-cm spacing \((P = .1)\). However, qualitatively, ablation zones performed at the 2-cm spacing would often develop a bilobed appearance (Fig 3). In addition, overall, ablations performed at 1-cm spacing showed slightly improved circularity (0.85) compared with ablations performed at 2-cm spacing (0.78). Calculated volumes showed similar trends.

When comparing single versus paired-antenna ablations, there was a significant increase in transverse dimension and area at the 5-minute time point for the 1-cm and 2-cm spacings. Although there was a significant increase in length at the 2-cm spacing \((P = .002)\), this did not meet statistical significance for the 1-cm spacing \((P = .06)\). There was a significant increase in area and transverse dimension when comparing single versus paired antennae 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 the present study, we began to characterize a modified triaxial antenna created to generate short ablation zones in an in vivo porcine model. Although single antennas create relatively elliptical ablations, the length was approximately 4 cm despite continued growth of the transverse dimension over time. Paired antennas created more spherical ablations, with increased transverse dimension compared with single-antenna ablations, but with slightly less prominent increases in length. One-centimeter spacing appeared optimal as a result of increased clefting and decreased circularity seen at 2-cm spacing (Figs 2, 3).

Multiple series have reported microwave ablation zone lengths greater than 5 cm (Table 4) \((7-9,20,22)\) or qualitatively described elongated and somewhat

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**Table 1. Single Modified Triaxial Antenna Microwave Ablation Dimensions**

<table>
<thead>
<tr>
<th>Time</th>
<th>Length (cm)</th>
<th>Transverse Dimension (cm)</th>
<th>Area (cm²)</th>
<th>Volume (cm³)</th>
<th>Aspect Ratio*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 min (n = 16)</td>
<td>2.9 ± 0.45</td>
<td>1.8 ± 0.27</td>
<td>3.9 ± 1.0</td>
<td>4.9 ± 1.9</td>
<td>0.61 ± 0.09</td>
</tr>
<tr>
<td>5 min (n = 21)</td>
<td>3.5 ± 0.55</td>
<td>2.0 ± 0.32</td>
<td>5.3 ± 1.4</td>
<td>7.4 ± 2.9</td>
<td>0.57 ± 0.13</td>
</tr>
<tr>
<td>10 min (n = 13)</td>
<td>4.2 ± 0.4</td>
<td>2.5 ± 0.25</td>
<td>8.1 ± 1.5</td>
<td>14.2 ± 3.3</td>
<td>0.59 ± 0.07</td>
</tr>
</tbody>
</table>

*Transverse dimension divided by length.

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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 (probe tract marked by arrow, a) to optimize length measurements. Note the somewhat spherical ablation zones, particularly at 5 min (b). (Available in color online at www.jvir.org.)
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 the present study show that a modified triaxial antenna is able to generate shorter ablation zones than those described in the literature with the use of other antenna designs.

When compared with data acquired in a similar in vivo model with the use of a single conventional triaxial antenna, the single modified triaxial antenna showed shorter ablation zone lengths (3.5–4.2 cm for the modified triaxial antenna 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 with 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 a result of 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, radiofrequency ablation zones generated under similar conditions (10). Similarly, Mulier et al (23) 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 cm to 4.4 cm were reported with a variety of devices, including straight water-cooled needles and “umbrella” or

Table 2. Paired Modified Triaxial Antenna Microwave Ablation Dimensions

<table>
<thead>
<tr>
<th>Time</th>
<th>Spacing (cm)</th>
<th>Length (cm)</th>
<th>Transverse Dimension (cm)</th>
<th>Area (cm²)</th>
<th>Volume (cm³)</th>
<th>Aspect Ratio*</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>1</td>
<td>4.2 ± 0.9</td>
<td>3.1 ± 1.0</td>
<td>11.2 ± 6.4</td>
<td>25.2 ± 25</td>
<td>0.72 ± 0.18</td>
</tr>
<tr>
<td>5 min</td>
<td>2</td>
<td>4.9 ± 1.0</td>
<td>4.4 ± 0.6</td>
<td>16.3 ± 4.1</td>
<td>50.5 ± 16</td>
<td>0.9 ± 0.21</td>
</tr>
<tr>
<td>10 min</td>
<td>1</td>
<td>4.8 ± 0.5</td>
<td>3.8 ± 0.4</td>
<td>14.3 ± 3.3</td>
<td>36.7 ± 9.1</td>
<td>0.79 ± 0.11</td>
</tr>
<tr>
<td>10 min</td>
<td>2</td>
<td>4.8 ± 1.0</td>
<td>4.5 ± 0.7</td>
<td>15.6 ± 6.2</td>
<td>50.8 ± 24</td>
<td>1.0 ± 0.322</td>
</tr>
</tbody>
</table>

*Transverse dimension divided by length.

![Figure 2](www.jvir.org) 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. (Available in color online at www.jvir.org.)

![Figure 3](www.jvir.org) 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. (Available in color online at www.jvir.org.)

Figure 2.
Figure 3.
deployable devices (23). In HCC and metastatic lesions, very little length data are reported, but one study that treated metastatic lesions (24) reported lengths of 3.4 cm ± 0.3 with the use of a 3-cm active zone water-cooled straight needle. The lengths seen with the modified triaxial antenna are similar.

The single-antenna ablations showed significant growth from 2 to 5 minutes and from 5 to 10 minutes, unlike radiofrequency ablations performed under similar conditions, which showed little growth between 5 and 10 minutes (10). This is most likely because of differences in heating mechanism (ie, volume heating with dielectric hysteresis vs conduction of current through increasingly charred, desiccated 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 ablation times, but this may be complicated by the possibility of increased tissue contraction for longer ablation times, which may decrease the final ablation zone size (25).

Although larger ablation zones, particularly in transverse dimension and area, were seen at 2-cm spacing compared with 1 cm, the differences seemed largely to have resulted from the additional separation and were not statistically significant at the 10-minute time point. In fact, because 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 (Fig 4). These data would suggest that 1-cm spacing is preferred.

Use of the antenna described here has been very promising in early clinical use, generating round, tip-weighted ablation zones as described in the in vivo model (Fig 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 used. However, for small tumors adjacent to vulnerable structures, a modified antenna

### Table 3. Single Versus Paired Antenna Microwave Ablation Dimensions

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Time (min)</th>
<th>Spacing (cm)</th>
<th>Length (cm)</th>
<th>Transverse Dimension (cm)</th>
<th>Area (cm²)</th>
<th>Volume (cm³)</th>
<th>P Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>5</td>
<td>NA</td>
<td>3.5 ± 0.55</td>
<td>2.0 ± 0.3</td>
<td>5.3 ± 1.4</td>
<td>7.4 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>Paired</td>
<td>5</td>
<td>1</td>
<td>4.2 ± 0.9</td>
<td>3.1 ± 1.0</td>
<td>11.2 ± 6.4</td>
<td>25.2 ± 25</td>
<td></td>
</tr>
<tr>
<td>Paired</td>
<td>5</td>
<td>2</td>
<td>4.9 ± 1.0</td>
<td>4.4 ± 0.7</td>
<td>16.3 ± 4.1</td>
<td>50.5 ± 16</td>
<td>.002*, &lt;.001†, &lt;.001‡</td>
</tr>
<tr>
<td>Single</td>
<td>10</td>
<td>NA</td>
<td>4.2 ± 0.4</td>
<td>2.5 ± 0.3</td>
<td>8.1 ± 1.5</td>
<td>14.2 ± 3.3</td>
<td></td>
</tr>
<tr>
<td>Paired</td>
<td>5</td>
<td>1</td>
<td>4.8 ± 0.5</td>
<td>3.8 ± 0.4</td>
<td>14.3 ± 3.3</td>
<td>36.7 ± 9.1</td>
<td>.02*, &lt;.001†, &lt;.001‡</td>
</tr>
<tr>
<td>Paired</td>
<td>10</td>
<td>2</td>
<td>4.8 ± 1.3</td>
<td>4.5 ± 0.7</td>
<td>15.6 ± 6.2</td>
<td>50.8 ± 24</td>
<td>.6*, .001†, .002‡</td>
</tr>
</tbody>
</table>

P values of single antenna vs paired antenna.
NA = not applicable.
*Length.
†Transverse dimension.
‡Area.

### Table 4. Selected In Vivo Microwave Ablation Zone Dimensions (7–9,20,22)

<table>
<thead>
<tr>
<th>Study, Year</th>
<th>System Parameters</th>
<th>Antenna (g)</th>
<th>Diameter (cm)</th>
<th>Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wright et al, 2005 (7)</td>
<td>915 MHz, 40 W, 10 min, H₂O cooling</td>
<td>13</td>
<td>Short axis 1.7 ± 0.4; maximum diameter, 2.4 ± 0.4</td>
<td>6.8 ± 1.0</td>
</tr>
<tr>
<td>Brace et al, 2007 (20)</td>
<td>2.45 GHz, 68 W, H₂O cooling</td>
<td>14.5</td>
<td>2 min, 2.3; 6 min, 2.6; 12 min, 2.9</td>
<td>NR</td>
</tr>
<tr>
<td>Awad et al, 2007 (8)</td>
<td>2.45 GHz, 100 W, 2–8 min</td>
<td>&gt; 6</td>
<td>Mean short axis: 2 min, 3.7 ± 0.6; 4 min, 3.8 ± 0.5; 8 min, 5.3 ± 0.6</td>
<td>Mean long axis: 2 min, 4.5 ± 0.9; 4 min, 4.9 ± 0.5; 8 min, 6.4 ± 1.1</td>
</tr>
<tr>
<td>Hines-Peralta et al, 2006 (9)</td>
<td>2.45 GHz, 150 W, 8 min</td>
<td>&gt; 6</td>
<td>In vivo short axis: 5.7 ± 0.2</td>
<td>6.5 ± 1.7</td>
</tr>
<tr>
<td>Ianitti et al, 2007 (22)</td>
<td>915 MHz, 45 W, 10 min</td>
<td>14</td>
<td>1.59 ± 3.5</td>
<td>NR</td>
</tr>
</tbody>
</table>

NR = not reported.
design such as a modified triaxial antenna could be used in cases in which, 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 or to treat small osseous lesions such as osteoid osteomas, or may be more practical for use in nerve ablation for chronic pain.

The present study was limited by the exclusive use of normal porcine liver rather than a tumor model or cirrhotic liver. Recent data generated with the use of a water-cooled 2.45-GHz system at 100 W (Amica; HS Medical, Boca Raton, Florida) suggest that the expected performance in human tumors can be expected to be somewhere between the performance seen in ex vivo and in vivo normal porcine livers (26). Sectioning of the ablation zones directly parallel and coronal to the applicator can be challenging and may introduce some variability of measurements. Also, in the present study, the antennas were tested in a single tissue type (liver), so translation into other tissues may require some additional study. In addition, all ablations were performed with a single microwave system and frequency.

The present 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.

Figure 4. Microwave ablation of a colorectal metastatic lesion. Preablation contrast-enhanced computed tomography (CT) image (a) demonstrates a small low-attenuation lesion (arrow) representing metastatic colorectal cancer. Intraprocedural noncontrast CT image (b) demonstrates two antennas spaced 2 cm apart (arrowheads). These were operated for 7 minutes at 65 W and created the bilobed ablation seen on the postcontrast, postablation 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 (star, d).
ACKNOWLEDGMENTS

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REFERENCES


Figure 5. Microwave ablation performed in a patient with cirrhosis and an 18 × 15-mm hepatocellular carcinoma. The preablation magnetic resonance image demonstrates arterial enhancement (a) and washout (b) within the tumor (arrow, a, b), consistent with hepatocellular carcinoma. Intraprocedural ultrasonography (c) again demonstrates the hyperechoic lesion (arrow), with the “steam cloud” encompassing the lesion (arrow, d). A single antenna was operated for 5 minutes at 65 W, creating a spherical ablation zone measuring 2.8 × 2.8 cm (arrow) as seen on axial postprocedure contrast-enhanced CT (e).