Title	Technological requirements for microwave ablation of adrenal masses
Author(s)	Fallahi, Hojjatollah; Shahzad, Atif; Clausing, Daniel; O'Halloran, Martin; Dennedy, Michael Conall; Prakash, Punit
Publication Date	2017
Publication Information	Fallahi, Hojjatollah, Shahzad, Atif, Clausing, Daniel, O'Halloran, Martin, Dennedy, Michael Conall, & Prakash, Punit. (2017). Technological requirements for microwave ablation of adrenal masses. Paper presented at the 11th European Conference on Antennas and Propagation (EUCAP), Paris, France, 19-24 March.
Publisher	IEEE
Link to publisher's version	https://dx.doi.org/10.23919/EuCAP.2017.7928268
Item record	http://hdl.handle.net/10379/15167
DOI	http://dx.doi.org/10.23919/EuCAP.2017.7928268

Technological Requirements for Microwave Ablation of Adrenal Masses

Hojjatollah Fallahi[1], Atif Shahzad[2], Daniel Clausing[1], Martin O'Halloran[2], M. Conall Dennedy[3], Punit Prakash[1*]
[1] Dept. of Electrical and Computer Engineering, Kansas State University, Manhattan, KS, USA, *prakashp@ksu.edu
[2] Dept. of Electrical and Electronic Engineering, National University of Ireland, Galway, Ireland, martin.ohalloran@gmail.com
[3] Clinical Sciences Institute, National University of Ireland Galway, Ireland, Michael.dennedy@nuigalway.ie

***Abstract*—Microwave thermal ablation is under consideration for minimally invasive treatment of bilateral adrenal adenomas, symptomatic of Conn's syndrome. Currently available microwave technologies are ill-suited to precise ablation of small adrenal targets. We report on our preliminary computational and experimental efforts towards the design of microwave ablation systems for targeting adrenal masses. Broadband dielectric properties of *ex vivo* bovine adrenal glands were experimentally measured. Computer simulations demonstrated the feasibility of achieving precise ablation of adrenal lesions with 2.45 GHz systems. Experiments in *ex vivo* adrenal tissue using a water-cooled 2.45 GHz antenna illustrated the feasibility of heating 10-20 mm adrenal targets with 40 W power applied for 1 min. These preliminary results warrant further investigation and development of microwave technology for precise ablation of adrenal masses.**

***Index Terms*—microwave ablation, dielectric properties, adrenal gland.**

I. Introduction

Primary aldosteronism (PA) is the commonest secondary cause of hypertension, accounting for 12-20% of all cases. It is characterized by excessive aldosterone production by unilateral or bilateral aldosterone producing adenomas. Current surgical treatment removes the entire adrenal gland and therefore treatment of bilateral disease is not amenable to this therapy due to inevitable adrenocortical insufficiency [1]. Therefore, there is a pressing need for improved, minimally invasive therapies which will definitively treat PA while preserving normal adrenocortical function. Thermal ablation provides one such option.

During a microwave ablation (MWA) procedure, the ablation antenna, typically enclosed in a needle or rigid catheter, is introduced into the target under ultrasound or CT image guidance. Microwave power radiated by the antenna is absorbed by surrounding tissue which leads to cell death at elevated temperatures. Many clinical studies have been reported on use of MWA for treatment of tumors in liver, lung, kidney, and breast [2]. Current MWA systems in clinical use operate at 915 or 2450 MHz. The latter frequency provides shorter antenna lengths, and more rapid heating [3].

Existing MWA systems have largely been optimized for creating large ablation zones, as is required for treating tumors in vascular organs such as the liver. Due to the small size of adrenal glands and adenomas, devices that afford creation of spherical ablation zones up to 10 mm in diameter are required. While it is possible to constrain ablation zone diameter perpendicular to the device insertion through careful selection of applied power and time, the ablation length is constrained by the antenna length.

The objective of this study is to report on our preliminary computational and experimental efforts towards the development of microwave antennas for ablation of adrenal masses at 2.45 GHz. Section II details the measurement of adrenal gland dielectric properties, numerical models utilized for antenna design, and antenna fabrication and evaluation setup. Results from dielectric measurement, simulation and device performance are provided in section III. In section IV, results are analyzed and discussed.

II. Materials and Methods

A. Measurement of dielectric properties

We employed the coaxial dielectric measurement technique to measure the broadband (0.5 – 20 GHz) dielectric properties of *ex vivo* adrenal glands [4]. Bovine adrenal glands were obtained from a local abattoir, within ~8 hours post mortem, and transported to the laboratory in sealed plastic bags. The temperature of the glands at the time of measurement was recorded at each site and found in the range of normal room temperature (22˚C±0.8). Dielectric measurements were performed using a slim-form dielectric probe (Keysight 85070E, Santa Rosa, CA, USA) connected to a vector network analyzer (Keysight E8362B). Measurements were performed on a total of 10 bovine adrenal glands. For each gland, measurements were performed at three randomly selected sites in each of the following regions: surface of the adrenal cortex; just below the adrenal cortex (by making a small incision on the adrenal gland surface); and in the adrenal medulla (i.e. total number of measurements on each gland = 9). Accuracy of the measurement system was evaluated on 0.1M NaCl solution, using the standard analysis technique described in [5], and combined expanded uncertainties for dielectric constant and conductivity are found as 0.63 and 2.71, respectively.

B. *Antenna design*

For this initial investigation of adrenal MWA, we selected a dielectric-loaded coaxial monopole antenna. Due to the application requirement of short ablation zones, we considered an operating frequency of 2.45 GHz. Water was selected for dielectric loading due to its high permittivity (ε_r ~78 at 2.45 GHz) and also because it serves as a means to actively cool the coaxial cable, thereby limiting passive heating along the length of the device.

C. *Computer models of adrenal MWA*

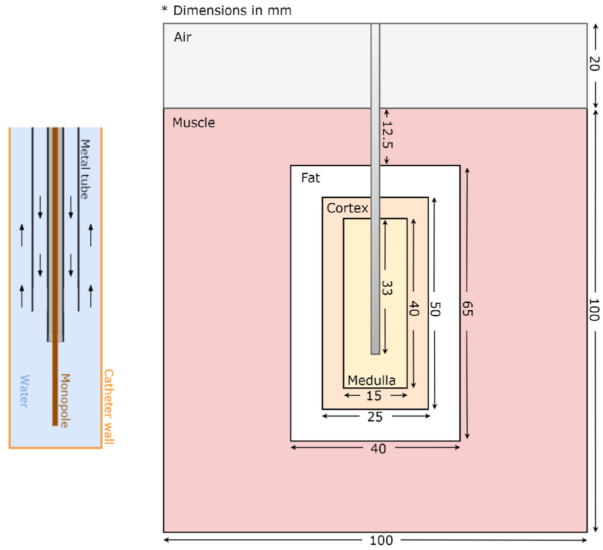
To aid in the design and optimization of applicators for adrenal ablation, we implemented 2D electromagnetic-thermal simulations. These simulations were employed to comparatively assess the efficacy of various antenna designs and microwave energy delivery patterns on power absorption patterns within adrenal tissue. Dielectric properties of adrenal tissues from experimental measurements were used as inputs to the computational model. Details of the computer model are described in [3], and summarized below.

A commercial FEM solver (COMSOL Multiphysics v5.1, COMSOL, Inc., Burlington, MA, USA) was used to model the electromagnetic radiation of the device and evaluate heat transfer within adrenal tissue. For the coupled electromagnetic and heat transfer simulation, static tissue properties of adrenal gland, fat, and muscle were taken from ITIS database [6]. Measured electrical permittivity and conductivity values were incorporated in the simulation for modeling the medulla and cortex. Fig. 1 shows the model which consists of four sections of medulla, cortex, fat and muscle with radii of 7.5, 12.5, 20 and 50 mm, respectively.

D. *Antenna farbication and experimental evaluation*

The water-cooled coaxial monopole antenna was fabricated as the MWA antenna, tuned to work at 2.45 GHz by choosing 6 mm length for monopole antenna tip. Fig. 1 shows different parts of the antenna. It consists of UT-34 semi-rigid coaxial cable, stainless steel metallic tubing (1.82 mm O.D. and 1.37 mm I.D.) as water inflow channel, and Polyimide tubing with 2.46 mm O.D. (~13 gauge) as a rigid catheter to enclose the applicator and water outflow channel. Fig. 2 shows the fabricated antenna.

Bovine adrenal glands were obtained from a local slaughterhouse and were delivered to the lab in sealed plastic bags inside a foam cooler box. In order to minimize the stray radiation during ablation and also provide a similar environment to *in vivo* settings, each adrenal gland was sandwiched between fresh pork loin tissues to mimic electromagnetically lossy tissue surrounding the adrenal gland within the body. Adrenal glands and pork loins were warmed to 35 °C prior to each experiment in order to emulate body core temperature.



(a) (b)

Fig. 1. Illustration of the (a) antenna tip and (b) geometry employed for 2D computational model.

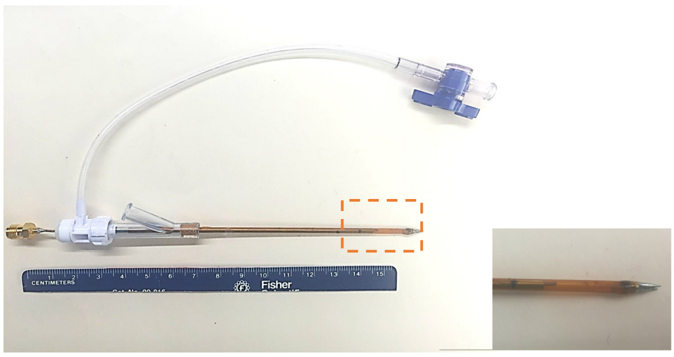


Fig. 2. Fabricated water-cooled monopole MWA applicator.

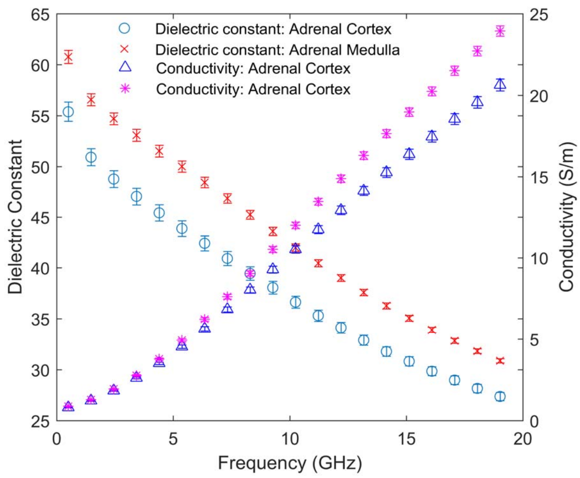
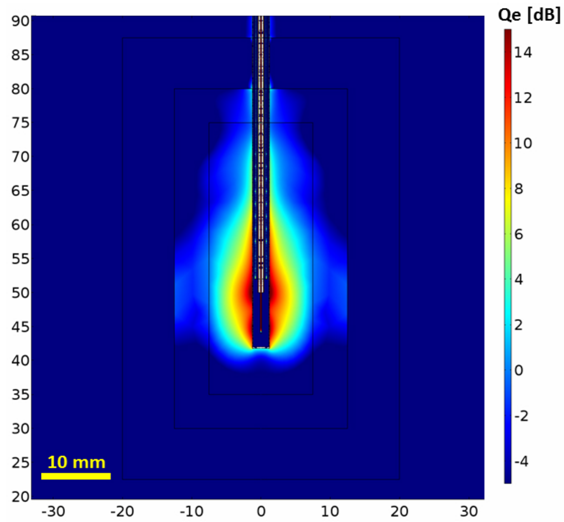
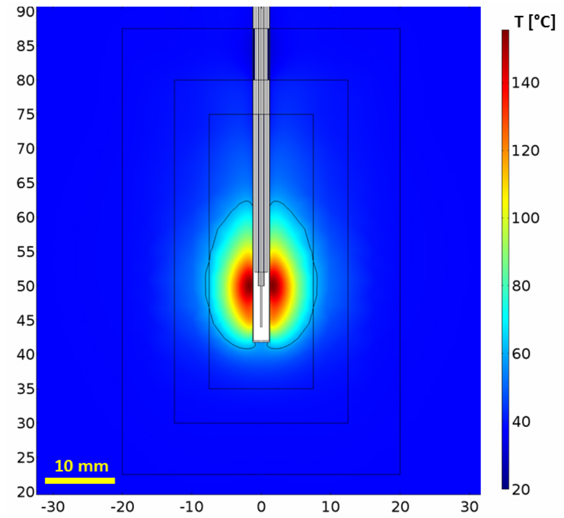


Fig. 3. Measured dielectric constant and conductivity of adrenal cortex and medulla at room temperature (~22 ˚C).



(a)



(b)

Fig. 4. Simulated (a) electromagnetic power loss density and (b) temperature profile for the water-cooled monopole antenna in *ex vivo* bovine adrenal gland sandwiched between porcine muscle for input power of 40 W at 2.45 GHz. Temperatoure contour of 60 ˚C is shown as an estimate of the ablation zone.

III. Results

A. Dielectric measurements

Fig. 3 shows measured dielectric constant and effective conductivity of the adrenal cortex and medulla at room temperature (~22˚C), with error bars showing standard error of the mean dielectric properties. Average dielectric contrast between adrenal cortical tissue and medulla was found to be ~13.5% in dielectric constant, and ~12.3% in the conductivity. Table I presents the dielectric properties of the bovine adrenal tissue at 2.45 GHz. A relatively higher contrast in both dielectric constant and conductivity is observed at higher frequencies.

TABLE I. Dielectric Properties of Adrenal Tissue at Ablation Frequency.

Frequency	**Dielectric properties**		
	Tissue	***Dielectric constant***	***Conductivity (S/m)***
2.45 GHz	Adrenal medulla	54.7	1.9
	Adrenal cortex	48.8	1.8

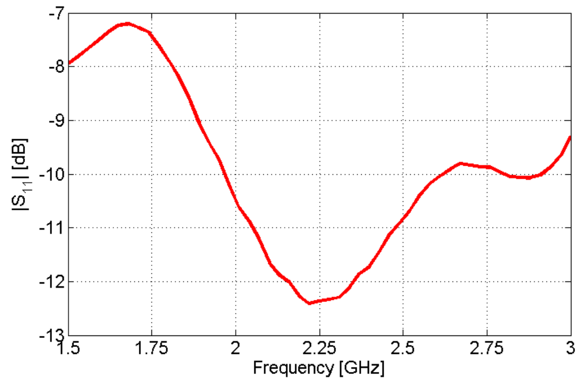


Fig. 5. Experimentally easured return loss of the water-cooled monopole antenna in *ex vivo* tissue.

Fig. 6. Cross section of the ablation zone on a sample bovine adrenal gland. Edge of the ablation zone is annotated with a dashed line.

B. Computer simulations

Fig. 4(a) shows the simulated electromagnetic power loss density normalized to 10^6 W/m^2 for input power of 40 W at frequency of 2.45 GHz. The reflections in the profile are due to the large permittivity difference of fat layer around the adrenal gland with other tissues. Simulated temperature profile of the model after 1 minute is observed in fig. 4(b). By considering 60 ˚C contour as ablation zone boundary, approximate width and length of the ablation zone are 10 and 20 mm, respectively.

C. Experimental results

Fig. 5 shows the experimentally measured return loss of the fabricated water-cooled monopole antenna, which is well suited to operation at 2.45 GHz ($S_{11} < -10$ dB). Fig. 6 shows a cross section of the ablation zone on one adrenal gland sample. The ablation zone is indicated by yellow dashed lines on the figure. Ablation diameter and height from $n = 3$ experiments in *ex vivo* tissue were: diameter: {11, 13, 12} mm and height: {20, 16, 23} mm.

IV. Discussion and Conclusions

This study was undertaken to design an antenna for a minimally invasive MWA of bilateral adrenal adenomas, symptomatic of Conn's syndrome. The small size of the gland and target adenomas (~10 mm sphere), make existing MWA devices, which have been developed for creating large ablation zones, unsuitable. Dielectric properties of different zones of adrenal glands were measured to provide the realistic parameters for MWA applicator design. A simulation-based approach was used to determine suitable antenna parameters, using a heterogeneous model containing different layers of adrenal gland and surrounding tissues. The objective of the optimization process was to design antennas that yield suitably small ablation zone dimensions, and minimize reflected power at 2.45 GHz. Water flow was incorporated in the antenna design in order to mitigate the effects of unwanted heating along the feed coaxial cable as well as minimizing the antenna radiating length.

The proposed device was fabricated and used to ablate three bovine adrenal gland samples. Measured dimensions of the ablation zone (mean diameter = 12 mm, mean height = 19.7 mm) were in good agreement with estimated ablation zone from simulations (diameter = 10 mm, height = 20 mm). Compared to MWA applicators in current use, where ablation zone length is typically ~30-40 mm [7], the proposed device affords improved control in heating along the length of the applicator. Further studies investigating modified antenna geometries to further reduce heating along applicator length are warranted. Another promising approach to reduce length of ablation zones is to design the system to operate at a higher frequency [8]. An advantage of operating at higher frequencies is the increased contrast in tissue dielectric properties (between the adrenal cortex and medulla), which may improve ability to localize power deposition within the targeted tissue.

In conclusion, the results of this pilot study demonstrate that percutaneous MWA may be suitable for thermal ablation of benign adenomas in adrenal glands. In addition to further investigation and optimization of antenna designs, future efforts should characterize the relationship between applied power levels and ablation duration on ablation zone size. Finally, *in vivo* studies with optimized devices should be conducted to assess the impact of thermal damage in the peri-ablational zone on adrenal function.

Acknowledgment

The research leading to these results has received funding from the European Research Council under the European Union's Horizon 2020 Programme/ERC Grant Agreement BioElecPro n. 637780. We also acknowledge funding through the KSU Johnson Cancer Research Center and the support of COST Action TD1301 and BM1309 EMF-MED for the convened session.

References

[1] W. F. Young, "Primary aldosteronism: renaissance of a syndrome," *Clin. Endocrinol. (Oxf.)*, vol. 66, no. 5, pp. 607–618, May 2007.

[2] J. I. Hernández, M. F. J. Cepeda, F. Valdés, and G. D. Guerrero, "Microwave ablation: state-of-the-art review," *OncoTargets Ther.*, vol. 8, pp. 1627–1632, Jul. 2015.

[3] S. Curto, M. Taj-Eldin, D. Fairchild, and P. Prakash, "Microwave ablation at 915 MHz vs 2.45 GHz: A theoretical and experimental investigation," *Med. Phys.*, vol. 42, no. 11, pp. 6152–6161, 2015.

[4] M. A. Stuchly, T. W. Athey, G. M. Samaras, and G. E. Taylor, "Measurement of Radio Frequency Permittivity of Biological Tissues with an Open-Ended Coaxial Line: Part II- Experimental Results," *IEEE Trans. Microw. Theory Tech.*, vol. 82, no. 1, pp. 87–92, 1982.

[5] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz," *Phys. Med. Biol.*, vol. 41, no. 11, p. 2251, 1996.

[6] P. A. Hasgall *et al.*, *IT'IS Database for thermal and electromagnetic parameters of biological tissues. Version 3.0, September 1st. 2015.* .

[7] A. M. Ierardi *et al.*, "A new system of microwave ablation at 2450 MHz: preliminary experience," *Updat. Surg.*, vol. 67, no. 1, pp. 39–45, Mar. 2015.

[8] J. F. Sawicki, J. D. Shea, N. Behdad, and S. C. Hagness, "The impact of frequency on the performance of microwave ablation," *Int. J. Hyperthermia*, pp. 1–8, 2016.