URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Changes in the Dielectric Properties of ex-vivo Ovine Kidney Before and After Microwave Thermal Ablation

Niko Ištuk*(1), Anna Bottiglieri(1), Emily Porter(2), Martin O'Halloran(1) and Laura Farina(1)(3)
(1) Translational Medical Device Lab, National University of Ireland Galway, Galway, Ireland, https://tmdlab.ie/
(2) The University of Texas at Austin, Austin, USA
(3) CURAM, SFI Research Centre for Medical Devices, Galway, Ireland

Abstract

In this work, a comparison in terms of dielectric properties (i.e. relative permittivity and conductivity) between ablated and non-ablated kidney samples (N = 3) was conducted. Measurements before and after ablation (N = 54) were performed on three different tissues (cortex, outer medulla, inner medulla) of ex-vivo ovine kidneys across the frequency range of 500 MHz – 8.5 GHz. Results show that both relative permittivity and conductivity decrease after ablation because of the decrease of the water content in the tissue. In particular, the highest difference between pre-ablation and post-ablation was observed in the tissue characterised by the highest water content.

1 Introduction

Electromagnetic-based thermal ablation techniques, such as Microwave Thermal Ablation (MTA), are widely used in interventional oncology to locally remove cancerous tissue by inducing a cytotoxic temperature increase. MTA is safely adopted in clinical treatments of solid tumors in different organs; clinical MTA procedure have been widely adopted in the treatment of solid tumours such as hepatic tumours and renal cells carcinoma in non-surgical candidates [1,2]. The increasing clinical acceptance of MTA procedures leads to the need for a thorough characterisation of tissue changes occurring during the ablative process.

In MTA, an increase in temperature (up to 120 °C in the treated tissue) is induced by the electromagnetic energy absorbed by the tissue. Complete necrosis of the tissue is achieved almost instantaneously when temperatures exceed 60 °C [1–3]. The rapid decrease of water content and the protein denaturation occurring in ablated tissues correspond to distinctive changes in the electromagnetic, thermal, and mechanical properties [3,4]. The interaction between the deployed electromagnetic energy and the tissue is primarily determined by the specific dielectric properties of the tissue. Accordingly, accurate information about the changes in dielectric properties of the tissue with the temperature increase are needed to optimize the treatment outcomes and better predict the induced thermal ablation zone [5,6]. This information also helps to support the development of novel non-ionizing monitoring techniques [7].

An accurate broadband characterization of the dielectric changes occurring during thermal ablation and in the ablated tissues is not available in the literature. A number of studies have been conducted to characterize liver tissue at physiological and hyperthermic temperatures [8–10]; whereas dielectric properties of kidney have been extensively investigated mainly at body temperature [11], and only limited data are available at hyperthermic temperatures and only for selected frequencies [4,12].

In this contribution, we propose a preliminary investigation of the changes in dielectric properties occurring in kidney tissues due to a MTA procedure. The dielectric properties of ablated and non-ablated ex-vivo ovine kidney tissues are measured with the open-ended coaxial probe technique and compared across the frequency range 500 MHz – 8 GHz. This frequency range covers the frequencies of the MTA applicators used in the clinical practice: 915 MHz and 2.45 GHz. It also covers recently investigated operating frequencies, such as 5.8 GHz, which allow miniaturization in the design of the MW applicator enabling smaller and more focused ablation zones [13].

2 Materials and Methods

Ovine kidneys (N = 3) were excised from sheep and were obtained the same day from a local abattoir. The samples were ablated with a fully cooled triaxial-based monopole antenna optimized to operate at 2.45 GHz [14]. The applicator was connected to a peristaltic dispensing pump (DP2000, Thermo-Fisher Scientific Inc, Waltham, Massachusetts, US) operating at 19.4 ± 1.2 °C and at a flow rate of 40 ml/min. A microwave generator (Sairem, SAS, France) was connected through a low-loss coaxial cable (50 Ω characteristic impedance) to the SMA connector of the applicator. Three ablation procedures (one ablation for each sample) were performed powering the applicator at 30 W for 1 min. The baseline temperature of the samples was 22.2 ± 0.8 °C. During the ablation procedure, the temperature was monitored via two fiber optic sensors (Neoptix Inc., Québec, CA) placed on the transversal plane of the applicator at a distance of 4 ± 0.4 mm from the antenna feed. The fiber optic sensors were used to ensure that a temperature of at least 60 °C was reached [1].

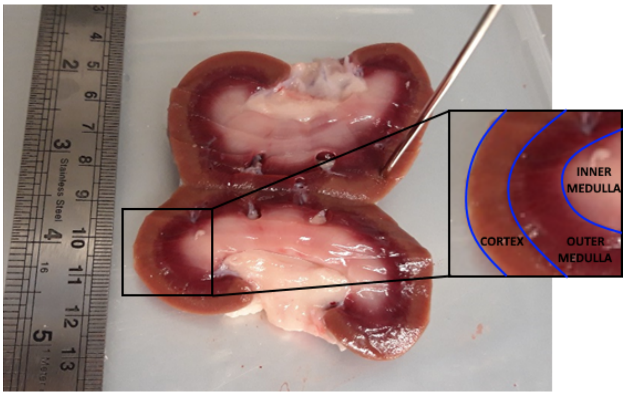


Figure 1. Three distinct tissues inside the kidney: cortex, outer medulla and inner medulla. All tissues have different histological composition and water content. Different colour of each tissue makes them distinguishable.

As shown in Fig. 1, three different tissues can be distinguished inside the kidney: cortex, outer medulla and inner medulla [16]. As these tissues are different in terms of histological composition and water content, relative permittivity (ε_r) and electrical conductivity (σ) were measured on each of the three types of tissues in the sample.

Fig. 2 shows one of the samples after the MTA. We can clearly see the ablation zone and we can verify that all three types of tissue are ablated. This was confirmed for all three samples.

The measurements of the dielectric properties (ε_r and σ) were performed using an open-ended slim-form coaxial probe (Keysight 85070E) connected directly to the vector network analyser (VNA Keysight 5063A) [17]. The measurement system uses a one port calibration method requiring three different loads: open circuit, short circuit and deionised water. The temperature of deionised water was 23.9 °C measured before the calibration. After the calibration, a 0.1 mol/L sodium chloride (NaCl) solution was used for the validation procedure; then the dielectric properties acquired during the validation were compared to the reference values reported in [19], and the percantage error is shown in Table 1. The validation procedure was repeated approximately every 30 minutes.

All of the measurements were performed acquiring 101 linearly spaced frequency points within 500 MHz – 8.5 GHz frequency range. Three consecutive dielectric properties measurements were performed on each tissue (N = 3) for each sample (N = 3) before and after the ablation procedure; in total 54 measurements were performed. The measurements were performed following the measurement protocol for characterization of dielectric properties of tissues [20]. All experimental data and associated metadata was collected in line with the Minimum Information for Dielectric Measurements of Biological Tissues (MINDER) guidelines for reporting of dielectric data of biological tissues [21].

Figure 2. Kidney sample after the MTA. The applicator was positioned so that the ablation zone partially covers all three tissue types: cortex, outer medulla and inner medulla.

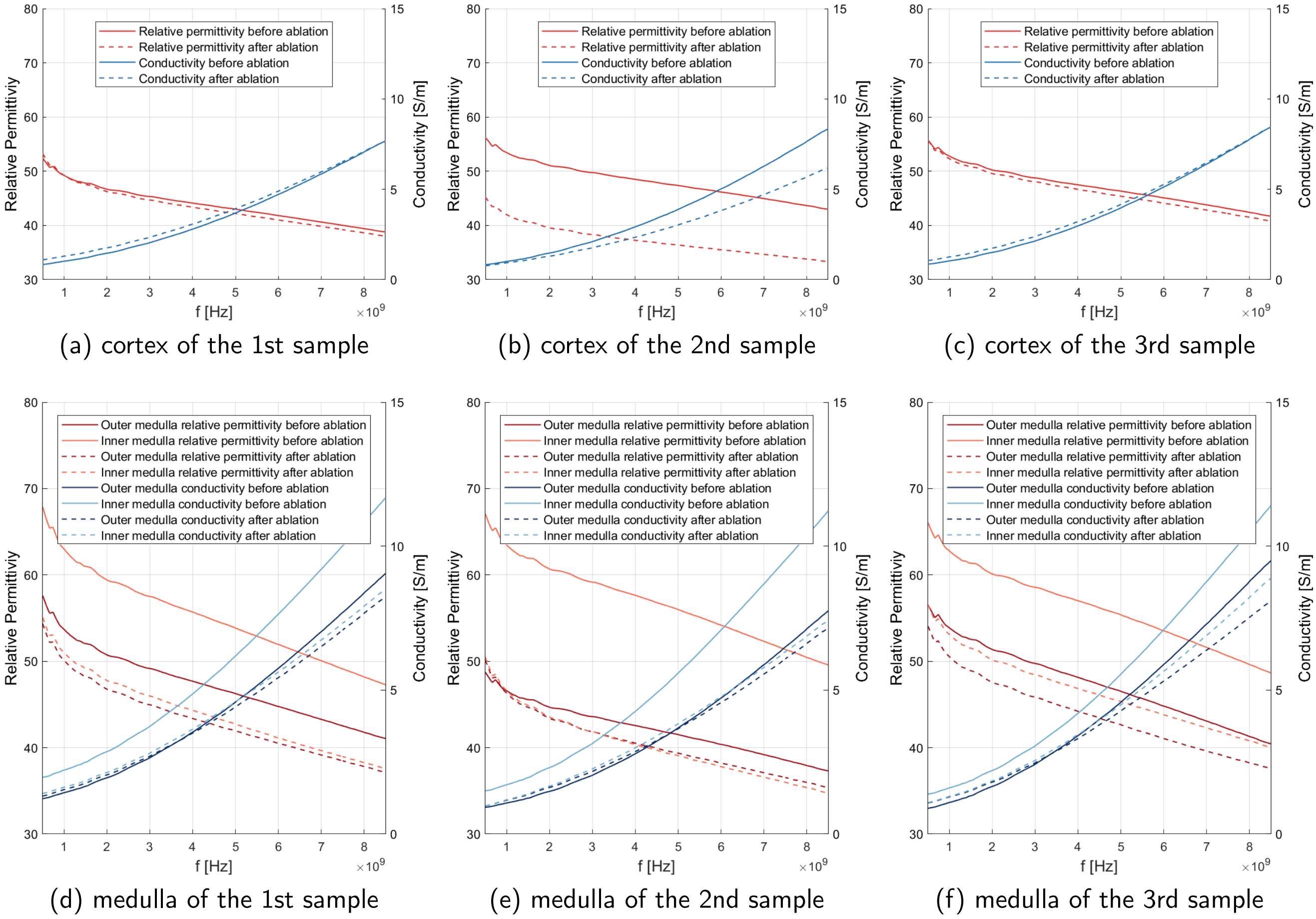
Table 1. The mean and the maximum value of the validation error in percentage.

	Mean error [%]	Max error [%]
Relative permittivity	1.96	3.52
Conductivity	2.41	10.19

3 Results and Discussion

The results of the measurements of the dielectric properties of three kidney samples before and after the ablation are shown in Fig. 3. The results are plotted as the average of the three consecutive measurements performed on each part of each sample. The relative permittivity is plotted in red, with values displayed on the left axis. Conductivity is plotted in blue and the conductivity values are on the right axis. The results of the measurements before the ablation are plotted with solid lines. The results of the measurements that were performed after the ablation are plotted in dashed lines. The results of the measurements on cortex tissue are in the first row and the results of the measurements on inner and outer medulla tissue are plotted in the second row. All subplots are plotted with the same values on both axes for comparison.

The values of the relative permittivity after the ablation are lower than before the ablation for every sample and for every tissue type (average difference in relative permittivity 5.55). The values of the conductivity of the cortex and of the outer medulla of all three samples mostly stay the same (average difference in conductivity 0.21 for cortex and 0.43 for outer medulla); while the conductivity of the inner medulla decreases after the ablation (average difference in conductivity 0.83).



(a) cortex of the 1st sample (b) cortex of the 2nd sample (c) cortex of the 3rd sample

(d) medulla of the 1st sample (e) medulla of the 2nd sample (f) medulla of the 3rd sample

Figure 3. Results of the dielectric properties measurements on three kidney samples. The columns correspond to one kidney sample each. The first is cortex and the second row is combined plots for inner and outer medulla. Red lines are relative permittivity and blue lines are conductivity. Solid lines are before the ablation and dashed lines are after the ablation.

The largest decrease in both relative permittivity and conductivity after the ablation is observed in the inner medulla. The inner medulla is the site where the urine drains into the renal pelvis, i.e. the initial part of the ureter [22]. Therefore, before the ablation, the values of the relative permittivity and the conductivity higher than the values in the surrounding tissues are observed in the inner medulla because of its higher water content. We can also see that the difference within tissue types in relative permittivity and conductivity is minimised after the ablation. The reduced range of properties is due to the fact that different tissue water content of the different tissue types mostly influences the dielectric properties of the tissues. After the ablation all the tissues are dehydrated and therefore the differences in tissue water content are minimised.

4 Conclusion

Dielectric properties measurements were conducted on ovine kidney tissue, distinguishing between cortex, outer medulla and inner medulla. The results suggest that both relative permittivity and conductivity decrease after the MTA treatment. We conclude that this change is mainly due to the decrease of water content in the tissues during the MTA. Indeed, the most significant change in relative permittivity and conductivity is observed for the tissue characterised by the highest water content, i.e. the inner medulla. We also observed that after the ablation all three tissue types have similar dielectric properties; the decrease in water content and the denaturation of proteins occurring during the ablation minimise the difference in the dielectric properties of the different tissue types.

5 Acknowledgements

This work has been developed in the framework of COST Action MyWAVE CA17115) and was supported by the EMERALD project funded from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 764479. This publication has emanated from research conducted with the financial support of Science Foundation Ireland (SFI) and is co-funded under the European Regional Development Fund under Grant Number 13/RC/2073. This project has received funding from the European Union Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n.713690. This project has received funding from the European Union

Horizon 2020 Programme (H2020)/ERC under the grant agreement n.637780.

References

[1] M. Ahmed et al., “Principles of and advances in percutaneous ablation,” *Radiology*, **258**, February 2011, pp. 351–69, doi: 10.1148/radiol.10081634.

[2] C.L. Brace, “Radiofrequency and microwave ablation of the liver, lung, kidney, and bone: what are the differences?,” *Current Problems in Diagnostic Radiology*, **38**, 3, May-Jun 2009, pp. 135-43, doi: 10.1067/j.cpradiol.2007.10.001.

[3] V. Lopresto et al., "Treatment planning in microwave thermal ablation: clinical gaps and recent research advances," *International Journal of Hyperthermia*, **33**, pp. 83–100, February 2017, doi: 10.1080/02656736.2016.1214883

[4] C. Rossmann et al., “Review of temperature dependence of thermal properties, dielectric properties, and perfusion of biological tissues at hyperthermic and ablation temperatures,” *Critical Reviews in Biomedical Engineering*, **42**, 6, pp. 467–492, 2014, doi: 10.1615/critrevbiomedeng.2015012486.

[5] V. Lopresto et al., "Microwave thermal ablation: effects of tissue properties variations on predictive models for treatment planning," *Medical engineering physics*, **46**, pp. 63-70, June 2017, doi: 10.1016/j.medengphy.2017.06.008.

[6] C.L. Brace, "Temperature-dependent dielectric properties of liver tissue measured during thermal ablation: toward an improved numerical model," *Proc 30th Annual International IEEE EMBS Conference*, p. 230–3, August 2008, Vancouver, British Columbia, Canada, doi: 10.1109/IEMBS.2008.4649132.

[7] G.G. Bellizzi et al., “A full-wave numerical assessment of microwave tomography for monitoring cancer ablation,” *11th European Conference on Antennas and Propagation (EUCAP)*, 2017, Paris, France.

[8] V. Lopresto et al., "Changes in the dielectric properties of ex vivo bovine liver during microwave thermal ablation at 2.45 GHz," *Physics in Medicine and Biology*, **57**, pp. 2309– 2327, March 2012, doi: 10.1088/0031-9155/57/8/2309.

[9] Z. Ji and C.L. Brace, "Expanded modeling of temperaturedependent dielectric properties for microwave thermal ablation," *Physics in Medicine and Biology*, **56**, 5249–64, August 2011, doi: 10.1088/0031-9155/56/16/011.

[10] G. Ruvio et al., “Comparison of coaxial open-ended probe based dielectric measurements on ex-vivo thermally ablated liver tissue,” 13th European Conference on Antennas and Propagation (EUCAP), 2019, Krakow, Poland.

[11] S. Salahuddin et al., “An anatomically accurate dielectric profile of the porcine kidney,” *Biomedical Physics Engineering Express*, **4**, 2, 025042, February 2018, doi: 10.1088/2057-1976/aaad7b.

[12] M. Pop, et al., “Changes in dielectric properties at 460 kHz of kidney and fat during heating: importance for radio-frequency thermal therapy,” *Physics in Medicine and Biology*, **48**, 15, pp. 2509–2525, Jul. 2003, doi: 10.1088/0031-9155/48/15/317.

[13] J.F. Sawicki et al., "The impact of frequency on the performance of microwave ablation", *International Journal of Hyperthermia*, **33**, 1, pp. 61-68, July 2016, doi: 10.1080/02656736.2016.1207254.

[14] L. Farina et al., "Microwave ablation antenna for functional adenomas in the Adrenal Gland", Proceedings of PIERS 2019 in Rome, 2019, Rome, Italy.

[15] S. Salahuddin et al., “Demonstration of dielectric heterogeneity of previously assumed homogeneous tissues: examination of the Heart,” in *12th European Conference on Antennas and Propagation (EuCAP 2018)*, London, UK, 2018, pp. 407 (5 pp.)-407 (5 pp.), doi: 10.1049/cp.2018.0766.

[16] M.H. Ross and W. Pawlina, “Histology: A Text and Atlas: WithCorrelated Cell and Molecular Biology, Seventh edition”, *Philadelphia:Wolters Kluwer Health*, 2016.

[17] T.P. Marsland and S. Evans, "Dielectric measurements with an open-ended coaxial probe," *IEE Proceedings H (Microwaves, Antennas and Propagation)*, **134**, 4, August 1987, pp. 341–349, , doi: 10.1049/ip-h-2.1987.0068.

[18] A. La Gioia et al., “Open-Ended Coaxial Probe Technique for Dielectric Measurement of Biological Tissues: Challenges and Common Practices,” *Diagnostics*, **8**, 2, p. 40, June 2018, doi: 10.3390/diagnostics8020040.

[19] A. Peyman et al., “Complex permittivity of sodium chloride solutions at microwave frequencies,” *Bioelectromagnetics*, **28**, 4, pp. 264–274, May 2007, doi: 10.1002/bem.20271.

[20] E. Porter et al., “Characterization of the Dielectric Properties of the Bladder Over the Microwave Range,” *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, **2**, 3, September 2018, pp. 208–215, doi: 10.1109/JERM.2018.2859584.

[21] E. Porter et al., "Minimum information for dielectric measurements of biological tissues (MINDER): A framework for repeatable and reusable data," International Journal of RF and Microwave Computer-Aided Engineering, **3**, 28, March 2018, e21201, doi: 10.1002/mmce.21201.

[22] K. Moore, "Clinically oriented anatomy," *LWW*, 2007, Philadelphia, USA