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Comparison of coaxial open-ended probe based dielectric measurements on ex-vivo thermally ablated liver tissue

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***Abstract*—This paper compares an in-house dielectric properties measurement system based on the "Stuchly and Stuchly" method with the broadly commercialised Keysight setup and existing literature for the characterization of ablated and non-ablated liver tissue. Measurements were carried out on *ex-vivo* ovine liver tissue across the frequency range 0.5 – 4.5 GHz. Results show that the in-house "Stuchly & Stuchly" method using calibration standards such as deionised water, methanol and open-circuit conditions, offers comparable performance to the proprietary Keysight system. Moreover, results are also comparable to measurements at 2.45 GHz documented in the literature. Being the in-house system suitable for portable setups as reported in the literature, this study shows that measurement of dielectric properties of tissue can be performed even during the thermal ablation procedure.**

***Index Terms*—ablation, dielectric measurement.**

I. INTRODUCTION

Microwave Thermal Ablation (MTA) is a minimally invasive technique used to cause death of cancerous cells by inducing a cytotoxic temperature increase (complete necrosis occurs almost instantaneously at temperatures in excess of 60 °C) in defined targeted regions. The localised thermal stimulus is generated by the absorption of electromagnetic energy in the microwave frequency range. This technique results in safe and effective clinical treatments of solid tumours as well as of gastroenterology tract and of lungs [1−3]. In particular, MTA treatments of liver carcinoma have become an established clinical procedure for non-surgically compliant patients [4]. This has allowed a large collection of data on the physical response of liver tissue to MTA. Moreover, the tissue homogeneity of liver tissue compared to other organs has suggested the opportunity to use this tissue as a common scenario to assess the performance of MTA applicators [5]. Further study is needed to improve the understanding of physical and biological modifications occurring in the treated tissue [6–9].

Most MTA applicators used in the clinical practice operate at 915 MHz or 2.45 GHz. Nonetheless, recent research has been devoted in higher operating frequencies with the aim to allow a higher degree of miniaturisation of the applicator (i.e. the microwave ablation antenna) or to generate smaller and more focused ablation zones [10]. The fast-growing clinical acceptance of MTA procedures justifies compelling research questions for a deeper characterisation of tissue change during the ablative process. MTA can induce temperature increases up to 120 °C in the treated tissue [11]. Two different regions can be identified in the thermally ablated area [12,13]: a central "carbonised" region, close to the antenna feed-point, where the temperature rises above 100 °C and the tissue appears charred, highly desiccated, and black; and a surrounding zone of coagulated tissue, also known as "white coagulation" region, where the temperature rises above 60 °C but without exceeding 100 °C [13]. The rapid decrease of water content and protein denaturation occurring in ablated tissues, correspond to distinctive changes in the electromagnetic, thermal, and mechanical properties [9–13]. However, at present, a broadband dielectric characterisation of ablated tissues is still incomplete. Such information is necessary to identify the contrast between ablated and non-ablated tissue, which could be exploited for improvement of MTA treatment planning as well as for real-time monitoring of the ablation zone [14]. To the authors' best knowledge, there is a limited number of works in literature reporting measurements of the dielectric properties of MTA-ablated tissues [13],[15−17].

This paper compares two broadband coaxial-probe based techniques to measure dielectric properties of ablated and non-ablated *ex-vivo* ovine tissue across the frequency range 500 MHz – 4.5 GHz. In particular, the Keysight dielectric measurement setup (i.e. Keysight E5071C ENA VNA with Keysight 85070E Dielectric Probe Kit and its dedicated software [18]) is compared to the "Stuchly and Stuchly" method using deionised water, methanol and open-circuit conditions as calibration standards [19]. The latter method has shown potential for being used as a portable non-proprietary setup that better suits the constraints of *in-vivo* measurements [20-21].

II. SETUP AND PROTOCOL

Fresh ovine liver tissue obtained from a local abattoir was ablated (on the same day) using an applicator consisting of a simple monopole antenna. The antenna was realised by exposing the 6 mm inner conductor of UT-047 coaxial cable (Micro-Coax Inc., Pottstown, PA, US), which was immersed in a water-cooled polyamide catheter with outer diameter of 2.3 mm. The length of the ablation applicator is 20 cm from the SMA connector to the feed-point (Fig. 1). The cooling system is generated by a peristaltic dispensing pump (DP2000, Thermo-Fisher Scientific Inc, Waltham, Massachusetts, US) operating at a flow-rate of 50 ml/min. The antenna was connected to a microwave generator (Sairem SAS, France) supplying an output power of 64 W at 2.45 GHz (CW), corresponding to 60 W at the antenna feed-point considering the loss of 1.9 dB/m at 2.45 GHz in the feeding cable. A total of four ablation procedures were performed on four tissue samples. Each ablation procedure had a duration of 2 minutes. The temperature of the ablated region was monitored during the ablation process with a fibre-optic temperature thermometer (Reflex Signal Conditioner, Neoptix, Inc., Quebec, Canada). A fibre-optic sensor was positioned at 5 mm from the antenna feed to ensure that a temperature of at least 90 °C could be measured in the tissue during ablation. No carbonization was observed in any ablated tissue sample. After completing ablation, the samples were let naturally return to room temperature.

Dielectric measurements were carried out in the frequency range from 500 MHz to 4.5 GHz. The setup included a vector network analyser (VNA) (Keysight E5071C ENA, Keysight Technologies, Inc., Santa Rosa, CA, USA), connected to an open-ended slim-form dielectric probe (Keysight 85070E), standard liquid samples (i.e. deionised water and methanol) and a fibre-optic thermometer. Before each measurement, the probe was cleaned with isopropyl alcohol, then the temperature of the samples and of the standard liquids was measured. The dielectric properties of the ablated tissue were measured by positioning the dielectric probe at six different locations within the zone of ablation, where the temperature of about 90 °C was measured during ablation. The dielectric properties of non-ablated tissue were also measured in eleven different positions across the samples. Both the proprietary Keysight software and an in-house software were used to assess the dielectric properties values derived from the dielectric probe reflection coefficient (S_{11}) measured by the VNA. In particular, in the latter case, measured S_{11} were collected and processed by an in-house code developed in Matlab™ evaluating the complex dielectric permittivity of the samples under test. The program implements the "Stuchly and Stuchly" method using deionised water, methanol and open circuit as calibration standards [19].

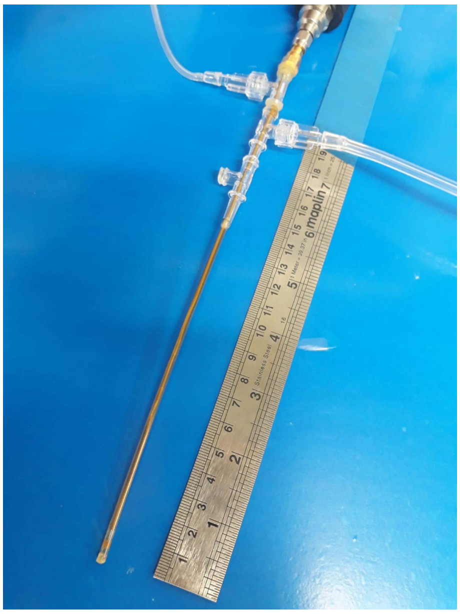

Fig. 1. Ablation applicator used in this study. The monopole antenna is created by exposing the inner conductor of UT-047 coaxial cable for a length of 6 mm immersed in a water-cooled polyamide catheter with outer diameter of 2.3 mm. The length of the ablation applicator is 20 cm from the SMA connector to the feed-point.

III. RESULTS

Fig. 2 shows the dielectric properties measured with the Keysight system as well as with the in-house "Stuchly and Stuchly" method in both ablated and non-ablated *ex vivo* liver tissues. Keysight data are reported in blue (ablated) and green (non-ablated), while "Stuchly and Stuchly" data are reported in red (ablated) and purple (non-ablated).

It can be observed from Fig. 2 that the in-house method can potentially match the expectations of the proprietary

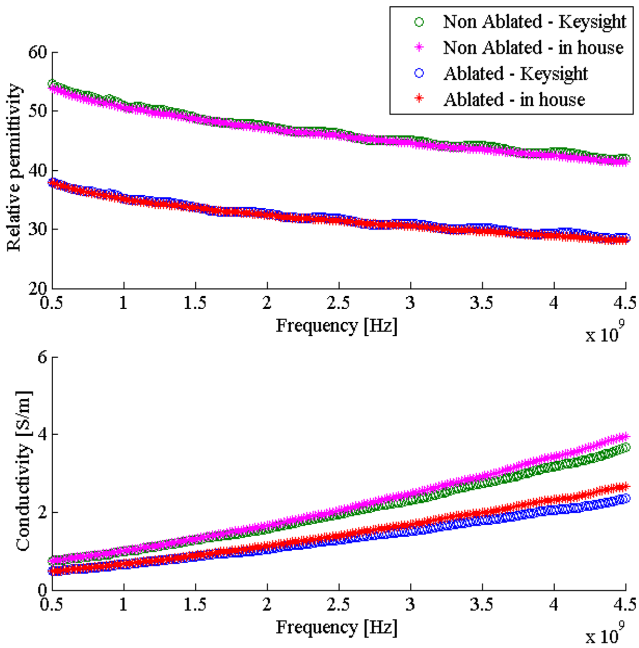

Fig. 2. Comparison of the "Stuchly and Stuchly" method with the Keysight method: dielectric measurements (mean values) as a function of frequency, performed in both ablated and non-ablated ovine liver with a slim-form probe connected to a VNA.

measurement software. With the “Stuchly and Stuchly” method, a smoother curve is also obtained, but slightly higher conductivity values (p-value > 0.05) are observable with the increase of the frequency, compared to values obtained with the Keysight software. The graphs report only mean values obtained as a function of the frequency, since no difference in the data variability was observed between the two different methods. Table I reports the average standard deviation of the measurements observed across the frequency range as percentage of the mean values measured.

Further, a drop of about 30% in the dielectric properties of ablated tissue with respect to the non-ablated tissue can also be observed in Fig. 2. The ablated data are collected from

TABLE I. DATA VARIABILITY: STANDARD DEVIATION REPORTED AS PERCENTAGE OF THE MEAN MEASURED VALUE (± ITS VARIANCE ACROSS THE FREQUENCY BANDWIDTH)

%	Ablated tissue		Non-ablated tissue	
	Relative permittivity	***Conductivity***	***Relative permittivity***	***Conductivity***
KS[a]	9.3 ± 0.1	14.5 ± 0.6	6.7 ± 0.1	9.6 ± 0.2
S&S[b]	9.3 ± 0.1	13.5 ± 1.1	6.7 ± 0.1	9.0 ± 0.5

a. *Keysight system*
b. *Stuchly & Sthucly method*

TABLE II. DIELECTRIC PROPERTIES OF THE ABLATED AND NON-ABLATED TISSUE AT 2.45 GHZ

2.45 GHz	Ablated tissue		Non-ablated tissue	
	Relative permittivity	***Conductivity [S/m]***	***Relative permittivity***	***Conductivity [S/m]***
KS[a]	31.9 ± 2.9	1.3 ± 0.2	46.4 ± 3.1	1.9 ± 0.2
S&S[b]	31.5 ± 2.9	1.4 ± 0.2	45.9 ± 3.0	2.0 ± 0.2

c. *Keysight system*
d. *Stuchly & Sthucly method*

four different ablations and no statistical difference has been observed between the different ablations (p-value > 0.07). The average difference in the relative permittivity of ablated and non-ablated tissue across the frequency bandwidth is 31.3 ± 0.4 %, with a slightly decreasing trend with the frequency in terms of absolute values (top Fig. 2). The average difference in conductivity across the frequency bandwidth is 34.2 ± 0.9 %, with a noticeably increasing trend in terms of absolute values as a function of the frequency (bottom Fig. 2). These results are comparable with those previously reported in literature [15 - 17], where an irreversible drop of the dielectric properties above 90 °C was noted. Specifically, values of relative permittivity below 35 and of conductivity below 1.55 S/m were observed at 2.45 GHz, in [15], whereas values of relative permittivity below 30 and of conductivity below 1.50 S/m were observed in [17]. For comparison, the dielectric properties measured in the present study at 2.45 GHz in liver tissue undergoing at least 90 °C are reported in Table II.

IV. CONCLUSIONS

Four ablations were performed in *ex-vivo* ovine liver tissue by ensuring that a temperature of 90 °C was reached in the target area. The dielectric properties of ablated tissue were measured over a broadband frequency range (0.5–4.5 GHz), by positioning the probe at six different locations within the zone of ablation. Likewise, dielectric properties of non-ablated tissue were measured in eleven different positions across the samples. Both the proprietary Keysight dielectric measurement system and the in-house developed code, based on the “Stuchly and Stuchly” method using open circuit, deionised water and methanol as calibration standards, were used to derive the dielectric properties from measured S_{11} data. Results showed no statistical difference between the two methods over the broadband frequency range of investigation for both ablated and non-ablated liver. Moreover, a comparison was also made with literature data at 2.45 GHz showing a good agreement.

To conclude, the in-house code proved its suitability to characterize the dielectric properties of ablated vs non ablated tissue over a wide frequency band. Since the in-house code can be used in portable setups where measurements are performed by means of a portable VNA, its use can be foreseen in more versatile applicative scenarios. In particular, information on the change of dielectric properties during ablation can be used to monitor the thermal procedure.

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