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Examination of the Sensing Radius of Open-ended Coaxial Probes in Dielectric Measurements of Biological Tissues

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***Abstract*—A number of emerging electromagnetic diagnostic and therapeutic devices are designed based on estimates of benign and malignant tissue dielectric properties at different frequencies and temperatures. Accurate tissue dielectric measurements are crucial for the development of these technologies. Although the dielectric measurement procedure is straightforward, several factors can introduce uncertainties and errors into dielectric data. These errors or confounders can be strictly related to the acquisition system or to the intrinsic properties of the investigated tissues. Generally, uncertainties are higher in the dielectric measurement of diseased tissues, due to their heterogeneity and complex structure and composition. These confounders can be minimized by clearly defining the measurement sensing volume, and characterizing the tissue distribution within that volume. The volume is defined by sensing depth and radius. In this work, early-stage experiments are presented to investigate the sensing radius for biological heterogeneous tissues, with the aim of providing more accurate dielectric measurements to support medical device development.**

Keywords*— biological tissues; dielectric properties; open-ended coaxial probe; sensing radius, electromagnetic medical technologies

I. MOTIVATION AND OVERVIEW

The interaction of electromagnetic (EM) fields with the human body is dependent on the inherent dielectric properties of each tissue. The open-ended coaxial probe is the most common technique used to measure the dielectric properties of biological tissues over a broad frequency range. Dielectric tissue measurements performed with an open-ended coaxial probe are affected by several factors, or confounders, which relate to two types of errors: equipment-related (or system) errors, and clinical errors. Although system errors have been thoroughly examined and compensated in several studies, no standard protocol has been defined to reduce or compensate for clinical errors.

Clinical confounders are related to the biological tissue heterogeneity and complexity and are responsible for increasing uncertainties in the dielectric measurements. These confounders mostly affect the dielectric measurement of diseased tissues. Diseased tissues typically show considerable variability in structure and composition [1], [2]. Unreliable or inaccurate dielectric data for diseased tissue could consequently affect the efficacy of EM medical devices that are designed based on these properties. For instance, accurate knowledge of the dielectric contrast between malignant and benign tissues in the microwave (MW) frequency range would contribute to the improvement of novel MW imaging systems, and therapeutic procedures, such as hyperthermia and MW ablation. The measurement issues related to tissue heterogeneity and complexity can be reduced by carefully selecting the tissue measurement region, and then histologically analyzing the tissue within that region after acquiring the dielectric data. A rigorous tissue characterization process, together with knowledge of the probe sensing volume, aims to create an accurate correspondence between histological and dielectric properties of biological tissues.

In the literature, there are a few studies investigating the probe sensing volume. While there are more works discussing the probe sensing depth [3]–[5], there is limited data regarding the probe sensing radius. For instance, Hagl et al. analyzed the effect of the beaker side on dielectric measurements of liquids at different radial distances [5]. Some dielectric experiments investigating the probe location on radially heterogeneous phantoms were performed [6], but no quantitative studies related to the probe sensing radius have been found in the literature.

In this work, early stage experiments are presented to investigate the probe sensing radius and how tissue heterogeneity in the radial sensing region can impact the acquired dielectric properties. The experimental plan and findings are described in the following sections.

II. MATERIALS AND EXPERIMENTAL METHODS

A. *Dielectric Measurement System and Validation*

In this study, tissue dielectric properties were measured using the Keysight slim form probe [7] (the most commonly used in recent works) connected to the Agilent E8362B network analyzer. The probe was calibrated using the three-load standard procedure. After each calibration, the system performance was validated by measuring the dielectric properties of 0.1 M NaCl, one of the most commonly used reference liquids [2]. The temperature of the calibration and validation liquids were recorded during each dielectric measurement. Recordings of 0.1 M NaCl confirmed the measurement uncertainty was less than 2%. For each liquid/tissue measurement, the relative permittivity and conductivity were acquired at 101 frequency points on a linear scale over the microwave frequency range of 0.5 - 20 GHz.

B. *Measurement Description*

For tissue measurements, pork meat obtained from a local butcher was used. Pork belly was chosen because of its well-defined heterogeneous structure consisting of two easily

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distinguishable tissues: fat and muscle. During the tissue measurements a firm contact between the probe and the tissue was established and the tissue temperature was measured with an infrared thermometer. Two different experiment sets were conducted:

- In order to qualitatively determine the probe sensing radius, measurements on both fat and muscle tissues were performed in two approximately-homogeneous regions of small and large size. The small sample region was approximately 1 mm larger than the 2.2 mm diameter probe, while the large region was approximately 10 mm larger than the probe. The small and large measurement regions in muscle are shown in Fig.1 (a).
- In order to verify the permittivity contribution of each tissue (present within the probe sensing volume) to the total permittivity signal acquired by the probe, dielectric measurements were performed at five points on three different tissue locations: fat, muscle, and fat/muscle edge. The probe position at the fat/muscle edge is shown in Fig.1 (b).

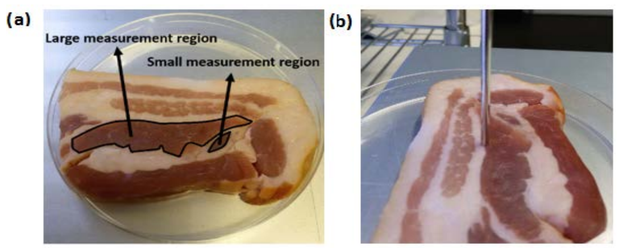

Fig. 1. (a) Muscle large and small measurement regions. (b) Probe position at the fat/muscle interface.

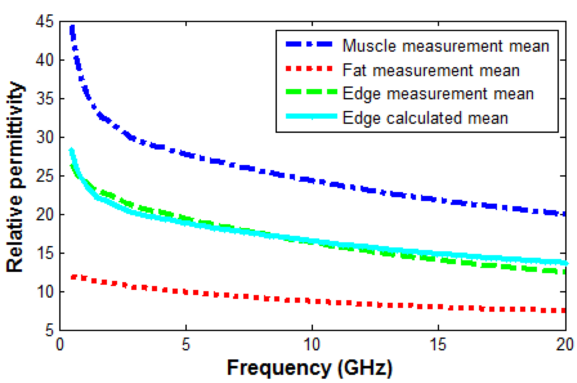

Fig. 2. Plot of the average permittivity calculated across five measurements on muscle, fat, and fat/muscle interface tissues over the range 0.5 - 20 GHz. The permittivity values of fat/muscle interface tissue are halfway between the permittivity values of muscle and fat tissues and very close to the permittivity values calculated by averaging the muscle and fat permittivity.

III. RESULTS AND DISCUSSION

From the analysis of the data obtained in the first set of experiments, differences within the uncertainty have been found between measurements performed within small and large approximately-homogeneous regions. This experimental outcome suggests that the probe sensing region is not much larger than the probe tip, although the Keysight probe datasheet recommends to position the probe at least 5 mm far from the tissue edge [7]. This finding appears to be consistent with the sensing radius analysis in Hagl *et al.*, where the authors concluded that for a 2.2 mm diameter probe a distance of 1.25 mm from the material edge was sufficient to avoid undesired reflections [5].

Furthermore, from the analysis of the data obtained in the second set of experiments, it has been observed that the two tissues included in the probe sensing radius contribute equally to the total dielectric signal acquired at the fat/muscle tissue edge. This experimental outcome was verified by comparing the mean permittivity value of the fat/muscle tissue interface measurements with the mean permittivity value obtained by averaging the permittivity values from the separate fat and muscle measurements. Fig. 2 shows that the difference between the measured permittivity mean at the fat/muscle tissue interface and the calculated permittivity mean is around 5%. This percent difference is within the tissue measurement standard deviation and confirms that muscle and fat tissues contribute equally to the dielectric properties measured at the fat/muscle tissue interface.

IV. CONCLUSIONS

Early experiments described in this work represent the basis for future quantitative investigation of the probe sensing radius. The aim of this work is to improve the dielectric characterization of highly heterogeneous tissues, such as animal and human diseased tissues. Because the sensing volume is affected by the intrinsic dielectric behavior of the investigated material, further experiments involving the analysis of different materials with specific complex structures across both radial and axial directions are needed.

To conclude, future studies investigating the probe sensing volume in biological tissues will contribute to accurate dielectric measurements and more precise EM medical device design.

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