2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

Challenges in the Dielectric Measurement of Heterogeneous Tissues: Impact of Uncertainty in Sensing Depth Calculation

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Abstract

The dielectric properties of biological tissues are parameters used in the design and development of microwave medical technologies. For example, knowledge of these properties is key in hyperthermia treatment planning, which has promise for improving outcomes in the treatment of cancer. In this study, we examine a source of error that can impact the accuracy of dielectric measurements, especially those of heterogeneous tissues. Specifically, we consider the determination of the sensing depth of the dielectric probe. As measurement uncertainty can be used as a threshold to define the sensing depth, we here investigate the impact of the measurement uncertainty on the resulting sensing depth value. This work demonstrates that the calculated sensing depth value can vary significantly with the magnitude of the uncertainty. Further, the results suggest that it is prudent to carefully measure the uncertainty value for each specific measurement scenario. With a better understanding of the calculated sensing depth of the probe under various circumstances, improved estimates of tissue properties can be obtained to support developing medical technologies.

1. Introduction

The dielectric properties of biological tissues are characteristic parameters that describe how electromagnetic fields interact with tissue. These properties vary across different types of tissues, and can change if tissue becomes diseased. Knowledge of the dielectric properties of tissues is therefore vital for the design and application of microwave medical technologies, including both diagnostics and therapeutics. However, there are many sources of error that can impact the accurate measurement of dielectric properties of tissues, and lack of understanding or control over these sources of error is a particular challenge in achieving accurate dielectric data for heterogeneous tissues. As such, inaccuracies in dielectric data provide a poor foundation for designing and using medical technologies.

In this work, we take the example of hyperthermia for treatment of cancer to describe the requirement for dielectric data. The objective of hyperthermia treatment is to increase the temperature in the tumour region (to ~43°C) while maintaining normal temperatures (37°C) in the surrounding healthy tissues. Prior to applying electromagnetic heating to the tumour, the treatment is carefully planned. During hyperthermia treatment planning (HTP), the first task is the generation of a patient model. During this step, the geometry and the dielectric properties of the treatment region must be identified. Limitations in planning can occur due to difficulty in both identifying the interfaces among tissues and in the quality of the dielectric property estimates for each tissue [1]. The dielectric properties of each tissue affect the resultant electric field and specific absorption rate (SAR) distribution, which, consequently, affects the temperature increase in the region of interest [1], [2].

The accuracy required is assessed before each treatment and depends on the specific application. For example, in the case of breast cancer, strong heterogeneities among breast tissues exist. Heterogeneities are significant for treatment planning, since, for example, fatty breast tissues and extremely dense breast tissues produce different results in terms of EM heating. Especially in the case of extremely dense breast tissues, wherein the heating zone varies considerably, having accurate dielectric properties is important for achieving more effective treatments [3].

If the assumed dielectric properties are inaccurate, the SAR distribution and the temperature increase in the treated region are both affected. The tumour region may not be targeted as effectively, and high temperatures could occur in healthy tissues (producing painful "hot spots") rather than in the target tissue. This issue could result in inefficiency of the hyperthermia treatment and in undesirable side effects for the patient.

Thus, it is clear that having accurate knowledge of dielectric properties, especially for heterogeneous tissue regions, can only support the refinement of treatment planning techniques and thus the treatment outcomes for patients. While the application of hyperthermia has provided an example, similar considerations exist in other microwave medical technologies. For these reasons, in this work, we investigate a source of error that may be impacting the accuracy of dielectric measurements of non-homogeneous tissues. Specifically, we investigate the

sensing depth of the coaxial probe that is used to measure the dielectric properties of tissues.
The sensing depth is defined as follows: It is the distance away from the probe tip at which the influence of a material is no longer detected in the dielectric data. However, to implement this definition, we need to quantify what is meant by "detected". Past studies have chosen a threshold that results in an acceptable amount of error in the magnitude of the relative permittivity [4]. Other studies have used the measurement uncertainty of the system as the threshold [5], [6]. In both of these cases, the sensing depth value would change based on how the threshold of detectability is defined. In this work, we discuss the impact of using measurement uncertainty in the sensing depth calculation. However, both "threshold" methods are effectively equivalent, and only vary based on how the exact value of the threshold of detectability is determined.

2. Methodology

Numerical simulations were performed in order to investigate the sensing depth of the open-ended coaxial probe. Simulations were conducted using COMSOL Multiphysics. The coaxial probe was modelled to match the Keysight slim form probe [7], with 2.2 mm diameter and 200 mm length. As the Keysight probe is fabricated using unknown conducting and insulating materials, in this study, materials of Teflon and Nickel were assumed as the insulator and conductor materials, respectively.

For this study, a 2D environment was simulated, as the probe and the materials involved are axially-symmetric. The dielectric properties of the various materials involved in this study were incorporated into the simulation using two-pole Debye models. For tissues, Debye models were fitted to the dielectric reference data from the IT'IS database [8]. After running the simulation, the resulting S-parameters were converted to complex permittivity, as in [9].

The simulation scenario is depicted in Figure 1. In the figure, a 'stack' of materials (denoted M1 and M2) is shown. By varying the thickness of M2, the dielectric properties of the stack, as measured by the probe, will vary. This information is used to calculate the sensing depth, as discussed at the end of this section.

In this study, we examine three different material scenarios, as summarized in Table 1. These scenarios are chosen so that results can be obtained with varying dielectric contrasts of M1 and M2, and with varying magnitudes of the permittivity of M1 and M2, as these parameters are expected to impact the sensing depth of the probe [4], [5]. The relative permittivity for each of the four materials used as either M1 or M2 is shown in Figure 2. For each scenario, simulations are performed for depths d spanning from 0 to 2 mm. The simulations were run over a frequency range of 500 MHz – 4.4 GHz (as a large bandwidth is needed to accurately convert S-parameters to permittivity); however, here only results for 500 MHz will be shown, as a representative example.

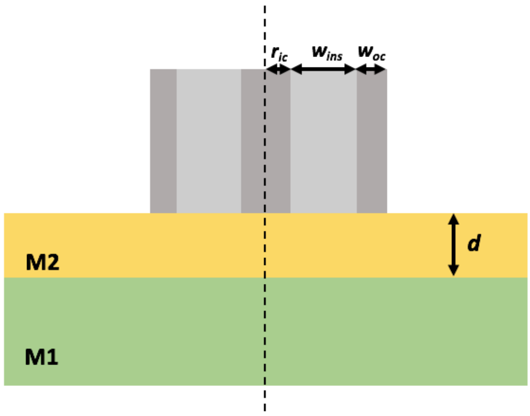

Figure 1. Diagram of simulation model. Material 1 (M1) is on the bottom (in green) and Material 2 (M2) is on the top (in yellow) of the material stack. The depth d is between the probe tip and the top surface of M1 (equivalent to the thickness of M2). The modelled probe (shown in grey), has inner conductor radius, r_{ic} = 0.25 mm; insulator width, w_{ins} = 0.5 mm; and outer conductor width, w_{oc} = 0.35 mm. The vertical dashed line indicates the axis of symmetry in the model.

Table 1. Summary of simulated scenarios.

	Case 1	Case 2	Case 3
M1	Teflon	Fat	Bone
M2	0.1 M Saline	Bone	Fat

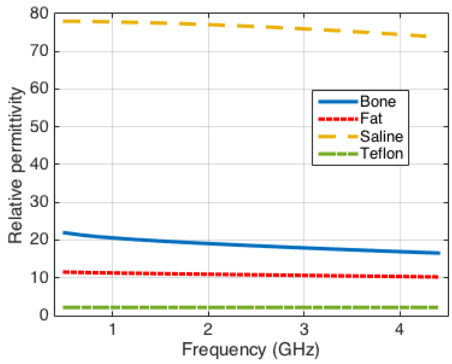

Figure 2. Modelled relative permittivity for bone (solid, blue line), fat (red, dotted line), saline (orange, dashed line), and teflon (green, dash-dot line).

Once the simulated data is obtained for each case and each depth d, the sensing depth of the probe can be determined. Specifically, the sensing depth is given by the depth d at which the influence of M1 can no longer be detected in the dielectric measurement to within the measurement uncertainty (in other words, the distance at which the dielectric measurement is equivalent to that of a measurement on a homogeneous sample of M2).

Typically, dielectric measurement systems are validated through measurements on standard liquid samples with well-known dielectric properties. Comparison of measured data to known model data enables calculation of the system uncertainty. However, the uncertainty for many measurement systems is also a function of the magnitude of the dielectric properties of the sample [7]. The exact magnitude of uncertainty depends on the measurement system and on the material measured. Here, we wish to examine the impact of varying uncertainty levels in the calculation of the sensing depth. Specifically, four levels of uncertainty are (arbitrarily) considered: 1%, 5%, 10%, and 20%. For coaxial probe measurements, 1% is an extreme lower limit for uncertainty, whereas 20% is a high limit. However, 5% and 10% are both realistic values when measuring complex biological materials, especially tissues.

3. Results

The curves of relative permittivity versus depth for each of the three simulated cases are shown in Figure 3. These plots are used to visualize the change in the contribution of M1 and M2 to the measured permittivity as d changes. Specifically, when $d = 0$ mm, the relative permittivity is equivalent to that of M1 in isolation. As d increases, both M1 and M2 contribute to the relative permittivity, until the depth at which the relative permittivity is equal to that of M2 in isolation. As can be seen from Figure 3, the shape of the curves depend on the magnitude of relative permittivity of both M1 and M2.

Next, the percent difference in relative permittivity is calculated for each d, relative to the final permittivity at maximum d of 2 mm (at this point, the measured relative permittivity is equal to that of M2 alone). The results are shown in Figure 4, and in Figure 5 with the uncertainty levels marked on the graph.

The sensing depth is then calculated based on Figure 5, where the sensing depth for a fixed case and a fixed uncertainty is given by the depth at which the uncertainty line intersects with the curve in question. The resulting sensing depth for each scenario is provided in Table 2.

From Table 2, it is evident that increasing the uncertainty decreases the resulting calculated sensing depth. Over all cases, going from 5% uncertainty to 20% uncertainty decreases the calculated sensing depth by an average factor of 2.5. Similarly, increasing from 1% to 20% uncertainty decreases the calculated sensing depth by a factor of 4.9 for Case 1, but a factor of 8 for Case 3. Even just increasing from 5% uncertainty to 10% uncertainty, the resulting calculated sensing depth changes by up to 36.9%. It is therefore clear that the sensing depth value is significantly dependent upon the uncertainty level used in the sensing depth calculation.

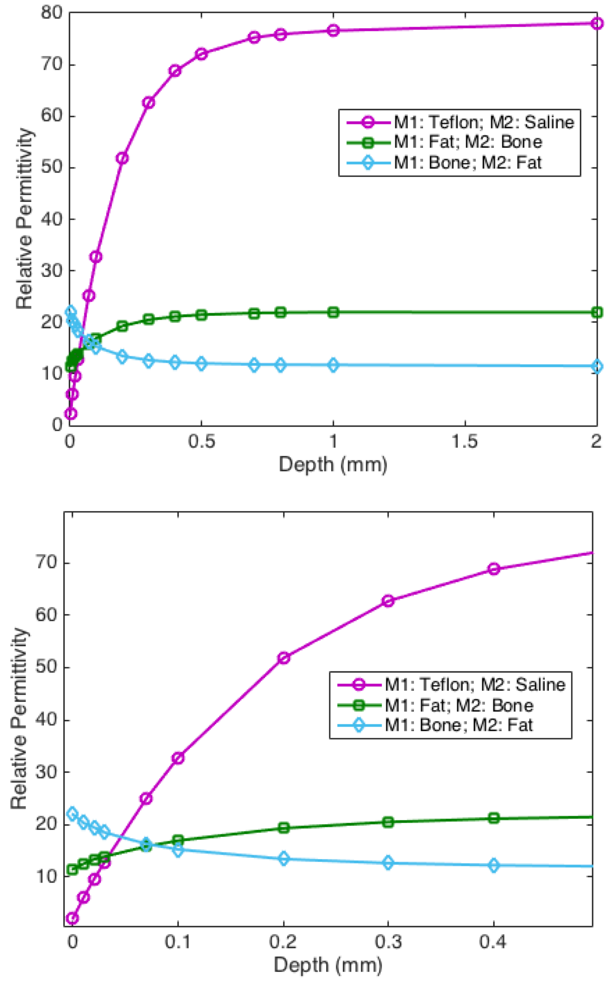

Figure 3. Plot of relative permittivity versus depth d for each of the three cases: for $d = 0$ to 2 mm (top) and zoomed-in (bottom). Case 1 is shown in purple, Case 2 in green, and Case 3 in blue.

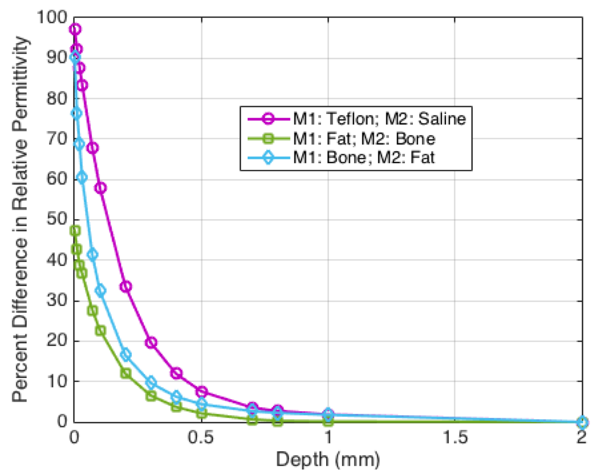

Figure 4. Percent difference in relative permittivity (relative to that of M2) versus depth d, for each of the three simulated cases. As d increases, the measured relative permittivity becomes closer to that of M2.

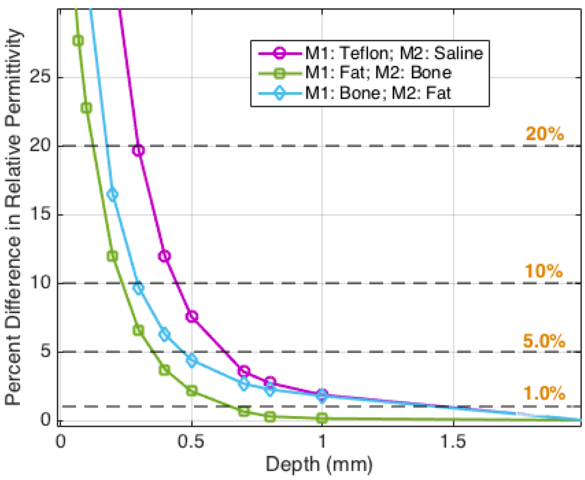

Figure 5. A zoomed-in version of Figure 4, with uncertainty levels of 1%, 5%, 10%, and 20% marked.

Table 2. Sensing depth (in mm) calculated using uncertainties (μ) of 1%, 5%, 10%, and 20%, for each case.

	μ = 1%	**μ = 5%**	**μ = 10%**	**μ = 20%**
Case 1	1.459	0.628	0.444	0.298
Case 2	0.651	0.355	0.237	0.125
Case 3	1.436	0.468	0.295	0.178

We note that the sensing depth will change based on the probe type that is used, especially if its diameter and the layout of conductors is varied. Therefore, the results provided in this study should be taken more as an example that can be adapted to any type of probe rather than as the exact result for any type of probe.

To conclude, this study has illustrated the importance of uncertainty in the calculation of the sensing depth for a coaxial probe. Specifically, when the sensing depth definition requires knowledge of the measurement uncertainty, the resulting sensing depth value is strongly influenced by the level of uncertainty. Effectively, when using a sensing depth in a dielectric study, researchers should carefully consider how they are calculating the sensing depth and that the calculation makes sense given the context of their study. It almost never makes sense to take sensing depth values provided in other studies, because the experimental setup will vary from study to study and the sensing depth from one will not be valid in another.

Accurate knowledge of the dielectric properties of biological tissues is important in the design and application of microwave medical technologies. Specifically, improving our understanding of sources of error in dielectric measurements can lead to solutions to reduce their impact, resulting in more accurate dielectric data for tissues. This improvement in accuracy in turn can support improved diagnostic and therapeutic technologies, and support better patient outcomes.

4. Acknowledgements

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, Science Foundation Ireland (SFI) grant number 15/ERCS/3276, and the Hardiman Research Scholarship. This work has been developed in the framework of COST Action MiMed (TD1301).

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