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<td><strong>Author(s)</strong></td>
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Quantification of the Sensing Radius of a Coaxial Probe for Accurate Interpretation of Heterogeneous Tissue Dielectric Data

Emily Porter, Member, IEEE
Alessandra La Gioia, Saqib Salahuddin, Martin O’Halloran, and Emily Porter, Member, IEEE

Take-Home Messages

- This work analyses the sensing radius of a coaxial probe for accurate dielectric characterisation of heterogeneous tissues.
- The probe sensing radius can be smaller than the probe radius and depends on the histology of the tissue sample.
- Accurate knowledge of the sensing radius has the potential for improving the design of novel microwave imaging devices and hyperthermia systems.
- This work demonstrates that a lack of knowledge of the probe sensing radius leads to errors in the interpretation of dielectric data acquired from heterogeneous tissues, and thereby to inaccurate medical device design.
- Despite the assumption made in previous dielectric studies, this work shows that the dielectric contribution of a particular tissue depends on both its location within the sensing volume and its dielectric properties.
Quantification of the Sensing Radius of a Coaxial Probe for Accurate Interpretation of Heterogeneous Tissue Dielectric Data

Alessandra La Giota, Saqib Salahuddin, Martin O’Halloran, and Emily Porter, Member, IEEE

Abstract: Accurate tissue dielectric measurements are crucial for the development of electromagnetic diagnostic and therapeutic devices that are designed based on estimates of the dielectric properties of diseased and healthy tissues. Although the dielectric measurement procedure is straightforward, several factors can introduce uncertainties into dielectric data. Generally, uncertainties are higher in the dielectric measurement of heterogeneous tissues, due to the fact that there is no standard procedure for acquiring and interpreting the dielectric data of heterogeneous tissues. Uncertainties related to tissue heterogeneity can be minimised by estimating the probe sensing volume, defined by the sensing depth and radius, and characterising the tissue distribution within that volume. While several studies have investigated the sensing depth, this work focuses on examining the sensing radius. Both dielectric measurements and numerical simulations with heterogeneous porcine tissues in the microwave range of 0.5-20 GHz have been conducted to quantify the sensing radius and the dielectric contribution of each tissue within the sensing volume. Experiments demonstrate that the sensing radius, which depends on the individual dielectric properties of the constituent tissue types, can be smaller than the probe radius. This work further quantitatively demonstrates that the dielectric contribution of a particular tissue depends on both its location within the sensing volume and its dielectric properties. This study provides fundamental knowledge for accurately interpreting dielectric data of heterogeneous tissues, with the aim of supporting medical device development.

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

I. INTRODUCTION

The interaction of electromagnetic (EM) fields with the human body is dependent on the inherent dielectric properties, namely the relative permittivity (εr) and conductivity (σ), of each tissue. The open-ended coaxial probe is the most common technique used for broadband measurement of dielectric properties of biological tissues. Dielectric tissue measurements performed with an open-ended coaxial probe can be affected by several factors, or confounders, which depend on the acquisition system, or the measurement protocol. Although system errors have been thoroughly examined, no standard protocol has been defined to reduce or compensate for errors associated with the characteristics of the investigated tissue sample. For this reason, heterogeneity and the complexity of biological tissues are the major confounders responsible for increasing uncertainties in dielectric measurements. Tissue dielectric data with high uncertainty could consequently affect the efficacy of EM medical devices that are designed based on this dielectric data. For instance, inaccurate knowledge of the dielectric properties of heterogeneous breast tissues, and of their dielectric contrast with tumour tissue in the microwave (MW) range, would compromise the design of novel MW imaging systems, and therapeutic procedures, such as hyperthermia.

Measurement errors related to heterogeneity can be reduced by carefully correlating the dielectric data to the histology of the tissues within the probe sensing volume. Historically, studies have investigated the probe sensing depth and its dependence on the dielectric properties of each tissue constituting the sample [1]–[5]. However, there is limited data available on the probe sensing radius, and only in Hagl et al. the sensing radius was estimated quantitatively [1]. Specifically, Hagl et al. found that the tissue sample width should be at least 5 mm for a 2.2 mm diameter probe. Lazebnik et al. applied the findings in [1] to determine the size of breast tissue slices to analyse histologically, where a 3 mm diameter probe was used and a 7 mm wide tissue region analysed histologically [6]. However, in Halter et al., although a smaller probe (diameter of 2.2 mm) was used, 10 mm wide tissue slices were analysed histologically for breast tissue dielectric characterisation [7].

From the studies in [6], [7], it is clear that there is no consensus regarding the size of the sensing radius (and thus the size of the histology region). Therefore, in this work, tissue measurements (additional to those already discussed in [8]) and novel numerical simulations are presented in order to quantitatively investigate the sensing radius. Due to...
the lack of studies investigating the sensing radius on heterogeneous tissue samples, dielectric measurements were performed on radially heterogeneous porcine samples consisting of fat and muscle tissues having different spatial distributions. These dielectric experiments were conducted in order to examine: i) how the sensing radius depends on the individual tissue dielectric properties; and ii) how the dielectric contribution of an individual tissue to the measured permittivity of the bulk sample depends on the individual dielectric properties of the tissue and its spatial distribution. The experimental findings were verified by numerical simulations that provided more quantitative information regarding the size of the sensing radius, and the contribution of each tissue constituting a radially heterogeneous sample.

II. EXPERIMENTAL SET UP

A. Measurement set-up

In this study, tissue dielectric properties were measured using the Keysight slim form probe [9], the most common probe used in recent works, connected to the Agilent E8362B network analyser. 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, a standard reference liquid [10], [11]. 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 consistently around 2.5%. For each liquid/tissue measurement, the relative permittivity and conductivity were acquired at 101 frequency points on a linear scale over the microwave range of 0.5-20 GHz.

For tissue measurements, porcine tissue obtained from a local butcher was used. Pork belly was chosen because of its well-defined heterogeneous structure consisting of two easily distinguishable tissues: fat and muscle. Tissue dehydration was minimised by limiting the exposure of each sample to the air. Prior to measurements, tissue samples were kept in hermetically closed containers and, between measurement times, the measurement sites were covered with excess tissue. During tissue measurement, each sample was brought to the probe tip using a lift table, a firm contact between the probe and the tissue was established, and the tissue temperature was measured with an infrared thermometer.

The dielectric measurements were then replicated numerically, as described in the following subsection.

B. Simulation set-up

Simulations were performed using COMSOL Multiphysics version 5.3, which solves electromagnetic wave problems using the finite element method (FEM). Before developing the probe model, dimensions of the Keysight slim form were measured. It was found that the inner conductor radius is 0.25 mm, the insulator width is 0.5 mm, and the outer conductor width is 0.35 mm, for a total probe radius of 1.1 mm and length of 200 mm. While the modelled probe dimensions match the size of the experimental probe, the Keysight probe insulator and conductor materials are unavailable to researchers. In this study, the insulator and conductor materials were assumed to be Teflon ($\varepsilon_r = 2.1, \sigma = 1e-23$) and Nickel ($\varepsilon_r = 1, \sigma = 1.43e7$), respectively, as they provided the best match between simulations and measurements relative to other tested materials.

According to the measurement scenario that the simulation was based on, either a 2D or 3D simulation environment was modelled. In particular, two probe models were developed: a 2D axisymmetric probe model (the symmetry axis is the long axis of the probe) that was used when the tissue distributions within the sample were axially symmetric, and a 3D probe model that was used for non-axially symmetric tissue samples. The use of a 2D axisymmetric model instead of a 3D model does not impact the simulation results, but it only reduces the computational cost. Due to the axially symmetry of the probe, the EM field distribution obtained from a 2D simulation can be mirrored across the symmetry axis to attain a full 3D field distribution.

The dielectric properties of fat and muscle tissues were assigned to the simulated tissues. The complex permittivity $\varepsilon(\omega)^*$, from which $\varepsilon_r$ and $\sigma$ were calculated, were obtained by fitting the two-pole Debye model to the average measured data from the porcine tissue samples. The parameters obtained by fitting the two-pole Debye model to the average measured fat and muscle tissue data were then used in the numerical simulations. These parameters are summarised in Table I.

For each numerical model, the coaxial EM source was positioned on the top of the probe, the absorbing conditions were assigned to the model boundaries, and the tetrahedral meshes were created. For the 2D simulations, the minimum and maximum mesh element sizes were 0.05 mm and 0.1 mm, respectively. Then, the mesh was further refined in the region close to the probe tip. Specifically, the mesh was twice as fine in the region defined by a 3 mm wide and 4.5 mm long bounding box centred at the probe tip. For the 3D simulations, the minimum and maximum element sizes were 0.1 mm and 0.3 mm, respectively. The 3D mesh is coarser than the 2D mesh due to limits in computational memory. Furthermore, 2D simulations were executed by the multifrontal massively parallel sparse direct solver (MUMPS), while 3D simulations were solved by the iterative biconjugate gradient stabilised method (BICGSTAB) due to the higher complexity of the 3D environment. Default settings were used for both solvers.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Muscle</th>
<th>Fat</th>
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<tr>
<td>$\varepsilon_r$ (S/m)</td>
<td>9.99</td>
<td>5.14</td>
</tr>
<tr>
<td>$\Delta \varepsilon_1$</td>
<td>41.05</td>
<td>1.73</td>
</tr>
<tr>
<td>$\tau_1$ (s)</td>
<td>3.06e-10</td>
<td>9.22e-11</td>
</tr>
<tr>
<td>$\Delta \varepsilon_2$</td>
<td>22.59</td>
<td>2.11</td>
</tr>
<tr>
<td>$\tau_2$ (s)</td>
<td>8.87e-12</td>
<td>9.27e-12</td>
</tr>
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Although the mesh element sizes and the solvers differed between the 2D and 3D simulations, results obtained from the same scenarios run in both environments were compared and the results confirmed to be consistent.

After the simulations were solved, the complex S11 parameters obtained from simulated samples were compared with the complex S11 parameters obtained from measured samples. A systematic S11 mismatch between simulations and measurements was found, likely attributable to differences in probe materials. However, the systematic mismatch error was compensated for by converting the S11 parameters into complex permittivity values, using the open-ended coaxial probe antenna model [12]. Specifically, the antenna model conversion algorithm uses known complex permittivity and corresponding complex S11 of three media to calculate the three parameters necessary to estimate the probe admittance that is linked to the permittivity. Deionised (DI) water, fat, and muscle were used as media for the estimation of the probe admittance. Details regarding mathematical modelling and formulation are reported in [12]. The converted permittivity was then compared with the measured permittivity; the results of which are discussed in Section IV.

III. METHODOLOGY

In this study, two types of experiments were performed. The first set of experiments was conducted to quantify the sensing radius and to investigate its dependence on the dielectric properties of the tissues constituting the sensing volume. Dielectric measurements on porcine tissues were conducted to qualitatively estimate the sensing radius; then, simulations were performed to quantitatively calculate the sensing radius. In the second set of experiments, the dielectric contribution to the bulk dielectric properties of each tissue within a radially heterogeneous sample was investigated. In particular, the dependence of the tissue dielectric contribution on the dielectric properties of each tissue and the spatial distribution of each tissue within the sensing volume was analysed.

A. Sensing radius investigation

Measurements

In order to qualitatively determine the sensing radius, in the previous work [8], measurements on both fat and muscle tissues were performed, with dielectric measurements taken in approximately-homogeneous regions of both small (about 0.1-0.5 mm larger than the 1.1 mm probe radius) and large (about 5-10 mm larger than the probe radius) size. In total, five different samples were used for this set of experiments. Details on the measurement procedure are reported in [8]. However, an example of the small and large regions of muscle measured on a porcine tissue sample is illustrated in Fig. 1.

For each sample, the permittivity values from the small and large approximately-homogeneous regions were compared in order to verify if the outer tissue had any impact on the dielectric properties obtained from small measurement regions.

In order to quantitatively determine the sensing radius, a number of concentric fat and muscle tissue samples were simulated in 2D. The 2D axis-symmetric model is illustrated in Fig. 2, where a half radial cross section of the probe tip is shown in contact with a tissue sample.

In the literature, it has been confirmed that the sensing volume depends on the dielectric properties of the tissues within the interrogated sample [3], [4]. Therefore, the sensing radius was calculated for two concentrically heterogeneous sample types: a sample with muscle as the inner tissue and fat as the outer tissue (muscle in & fat out), and the other sample with fat as the inner tissue and muscle as the outer tissue (fat in & muscle out). For each sample type, different geometries were examined: the radius of the inner tissue was gradually decreased from 2.5 mm to 0.5 mm in discrete decrements, while the width of the outer tissue was increased by the same size.

As discussed in Section II.B, for each simulation, the S11 parameters were converted into permittivity. Then, for each tissue sample type, the permittivity values calculated from all of the simulations were analysed and the sensing radius was calculated as the radius at which the outer tissue ceases to contribute to the dielectric properties, within the uncertainty of the measurement (i.e., the distance at which only the permittivity of the inner tissue is detectable, within the uncertainty of the measurement).

B. Tissue contribution investigation

In order to evaluate the dependence of the tissue contribution (to the total measured permittivity) on the spatial distribution of each tissue within the sensing
volume, measurements and simulations were performed on two configurations of radially heterogeneous samples: one consisting of fat and muscle tissues placed side-by-side, and the other one consisting of fat and muscle tissues arranged in a concentric pattern.

**Side-by-side tissue arrangement**

In order to verify the contribution of individual tissues to the total measured permittivity, when the tissues are arranged side-by-side, measurements and simulations were conducted on three different tissue locations: on only fat, only muscle, and at the fat/muscle interface, where both fat and muscle tissues occupy approximately 50% of the sensing volume. Five measurements were performed at each of the three locations and averaged. The same measurement procedure was repeated on three different porcine tissue samples exhibiting the same tissue distribution. The permittivity values were then examined to determine the contribution of the fat and muscle tissues to the total dielectric properties at the fat/muscle interface. The probe position at the fat/muscle interface of a porcine sample is shown in the left image of Fig. 4.

For a more precise evaluation of the contribution of the fat and muscle tissues to the dielectric data recorded at the interface, three 3D simulations were conducted: one with homogeneous fat, one with homogeneous muscle, and one with a radially heterogeneous sample composed of fat and muscle tissues placed side-by-side. The 3D model, with a sample composed of side-by-side fat and muscle tissues, is illustrated in Fig. 3. As illustrated in the figure, the probe was positioned exactly in the middle of the sample, where both fat and muscle tissues occupy 50% of the sensing volume. The S11 parameters obtained from each of the three samples (fat, muscle, and side-by-side fat and muscle) were converted into permittivity values. Then, the contribution of each tissue type to the dielectric properties of the radially heterogeneous sample was examined.

**Concentric tissue arrangement**

In order to verify the contribution of fat and muscle tissues arranged in concentric patterns to the total measured permittivity, dielectric measurements were conducted on five porcine samples composed of two types of concentrically heterogeneous tissue regions, one with muscle in & fat out, and the other one with fat in & muscle out. The inner and outer tissues of the concentrically heterogeneous regions were approximately-homogeneous. Also, the size of the inner tissue was considerably smaller than that of the probe. Specifically, the inner tissue had variable size across samples, with radii ranging from 0.5 mm to 0.9 mm (compared to the 1.1 mm of the probe radius). In Fig. 4, on the right, a concentrically heterogeneous region with muscle in & fat out is shown. In the figure, the size of the probe diameter (2.2 mm) is also included to better illustrate the size of the inner region occupied by the small approximately-homogeneous muscle tissue.

For each tissue sample, the average permittivity values from the concentrically heterogeneous measurement regions were compared with the average permittivity values from homogeneous fat and muscle regions in order to qualitatively estimate the dielectric contribution of the inner and outer tissues to the average measured permittivity from the concentrically heterogeneous tissue region.

Due to the difficulty of reproducing the tissue irregularities of the measured samples in the simulation environment, the measurements on the concentric samples were not replicated numerically in exactly the same way. Specifically, 2D axis-symmetric samples were modelled, since the measured samples were approximately axially symmetric. However, the irregular geometries of the measured samples were not reproduced due to the challenge of measuring them on a micrometer scale. In total, four 2D models were created: one with homogeneous fat, one with homogeneous muscle, and two with concentrically heterogeneous samples composed of fat and muscle tissues, one sample with fat in & muscle out and the other with muscle in & fat out. The 2D models used for this set of simulations are similar to the model described in Section III.A and illustrated in Fig. 2.

In particular, the radially heterogeneous concentric samples were modelled with a geometry such that both fat and muscle tissues occupied 50% of the sensing volume, in order to facilitate comparison with the results obtained from the side-by-side simulated fat and muscle tissues (both occupying 50% of the sensing volume). In order to ensure each tissue occupied 50% of the sensing radius, the radius of the inner tissue, and consequently the size of the outer tissue, were calculated. The inner tissue radius was obtained...
from knowledge of the sensing radius (estimated from the simulations in Section III.A), through:

\[
\frac{1}{2} \pi R^2 + \frac{1}{2} \pi R (R-r) = 1
\]

(1)

where \( R \) is the sensing radius, and \( r \) is the inner tissue radius. Solving (1), it was found that \( r_1 \) is equal to 0.71 mm for the sample with muscle in & fat out (when \( R \) is equal to 1 mm), and \( r_2 \) is equal to 0.64 mm for the sample with fat in & muscle out (when \( R \) is equal to 0.9 mm), since the size of the sensing radius is dependent on the permittivity of the individual tissues within the sensing volume.

Before showing measurement and simulation results, the experimental procedure followed for each investigation (sensing radius quantification, and tissue contribution estimation for side-by-side tissues and concentric samples) is schematised in Fig. 5.

![Flow chart summarising the experimental steps undertaken in each investigation: quantification of sensing radius for fat in & muscle out and muscle in & fat out samples, and estimation of tissue contribution for side-by-side tissues and concentric samples](image)

Fig. 5. Flow chart summarising the experimental steps undertaken in each investigation: quantification of sensing radius for fat in & muscle out and muscle in & fat out samples, and estimation of tissue contribution for side-by-side tissues and concentric samples.

IV. RESULTS AND DISCUSSION

In this section, measurement and simulation results from the sensing radius investigation are discussed, followed by results from the tissue contribution investigation.

A. Study #1: Sensing radius investigation

Measurement

From the measurements that investigate the sensing radius (an example of muscle tissue small and large measurement regions was provided in Fig. 1), the data acquired from fat and muscle tissues in the small sample region was compared with the fat and muscle data acquired in the large sample region. A subset of measured data is reported in [13] showing that the permittivity values obtained from small regions is within the range of values obtained from larger regions. Therefore, the boundaries of the small region do not significantly impact the measurement. This result demonstrates that, for fat and muscle tissues, the sensing radius is likely smaller than the size of the small regions that are approximately 0.1-0.5 mm larger than the 1.1 mm probe radius. More quantitative information is provided in the next subsection, where simulations results from the analysis of concentric fat and muscle tissue samples are discussed.

Simulation

In this subsection, the results from the simulations on the two concentrically heterogeneous samples described in Section III.A and modelled in Fig. 3 (one with fat in & muscle out, and the other one with muscle in & fat out) are analysed. In order to calculate the sensing radius for each concentric sample, the converted relative permittivity values from simulations with different inner tissue radii were compared to the relative permittivity values from the simulations consisting of homogeneous fat and muscle tissue samples. Thus, the relative permittivity values obtained from the simulated homogeneous fat tissue were used as reference data for the simulations involving concentric samples with fat in & muscle out, and the relative permittivity values obtained from the simulated homogeneous muscle tissue were used as reference data for the simulations involving concentric samples with muscle in & fat out. In particular, for each sample, the percent difference in relative permittivity between data from each of the simulations with variable inner tissue radius and the reference data was calculated at five different frequencies, as shown in Fig. 6 for the sample with fat in & muscle out.

As expected, the percent difference in relative permittivity decreases as the inner tissue radius increases. Also, the relative permittivity difference is higher at lower frequencies, as the sensing volume depends on frequency.

![Percent difference in relative permittivity at 0.5, 5, 10, 15, and 20 GHz between the simulated fat tissue (reference data) and the data from each of the 2D simulations with variable inner radius of fat tissue surrounded by muscle tissue (for the sample with fat in & muscle out). The calculated sensing radius, indicated with a black line, is 0.9 mm. Specifically, from the simulations, a sensing radius of 0.9 mm was found for the sample with fat in & muscle out, as indicated by the black line in Fig. 6, while a sensing radius of 1 mm was found for the sample with muscle in & fat out.](image)

Fig. 6. Percent difference in relative permittivity at 0.5, 5, 10, 15, and 20 GHz between the simulated fat tissue (reference data) and the data from each of the 2D simulations with variable inner radius of fat tissue surrounded by muscle tissue (for the sample with fat in & muscle out). The calculated sensing radius, indicated with a black line, is 0.9 mm.
the measurement uncertainty) from the reference data permittivity.

In summary, the simulations found that the sensing radius is, at most, 1 mm, although the probe datasheet recommends positioning the probe at least 5 mm far from an interface [9]. Also, the sensing radius estimated from this experimental study is 2.35 times smaller than the value reported in Hagl et al. [1]. However, the probe used in [1] was not the same probe used in this study. The sensing radius is likely to vary based on the design of a given probe, and definitely varies based on probe diameter. Furthermore, the results indicate that the sensing radius changes based on the dielectric properties of the tissues that occupy the sensing volume. In particular, the sensing radius appears to be smaller for tissues that have low permittivity. This effect may be due to the high impedance mismatch between the probe and the measured tissue that permits only a small part of the EM signal to reach the outer tissue.

B. Study #2: Tissue contribution investigation

Side-by-side tissue arrangement

Analysing data from side-by-side fat and muscle tissues reported in Fig. 4, on the left, it was observed that the two tissues within the sensing radius contribute equally to the dielectric data acquired at the fat/muscle interface. This experimental outcome was obtained by comparing the mean permittivity value of the fat/muscle interface measurements with the permittivity value obtained by averaging the permittivity values from the homogeneous fat and muscle measurements. The measurement data is reported and discussed in [8].

The measurement outcome was confirmed through simulations that accurately replicated the measurement scenarios. In Fig. 7, the real and imaginary parts of the complex S11 parameters obtained from 3D simulations of fat tissue, muscle tissue, and the heterogeneous sample composed of side-by-side fat and muscle tissues (which model is illustrated in Fig. 3) are plotted over the range of 0.5-20 GHz. From both the real and imaginary S11 plots, it can be observed that S11 parameters from the simulated fat/muscle interface tissue match well with the S11 values calculated by averaging the S11 parameters of the simulated homogeneous muscle and fat tissues for frequencies up to 5 GHz. At frequencies above 5 GHz, the average difference between the S11 parameters from the simulated fat/muscle interface tissue and the calculated mean S11 parameters is 15% for the real part and 11% for the imaginary part.

To have a complete insight of the simulation results, the relative permittivity values obtained from the conversion of the S11 parameters shown in Fig. 7 are plotted in Fig. 8. It is clear from Fig. 8 that the relative permittivity values obtained from the simulation at the fat/muscle interface tissue are equivalent to the permittivity values calculated by averaging the permittivity of the simulated homogeneous muscle and fat tissues, although the real and imaginary parts of the S11 parameters obtained from the fat/muscle interface tissue do not match perfectly with the calculated mean S11 values (as observed in Fig. 7).

Thus, from both measurements and simulations, it was observed that side-by-side tissues contribute equally to the acquired permittivity. The results of side-by-side tissue compositions are compared with the results from concentric tissue compositions in the following subsection in order to verify how the dielectric tissue contribution depends on the spatial distribution of the tissues occupying the sensing volume.

![Graph of real S11 parameters](image1)

![Graph of imaginary S11 parameters](image2)

Fig. 7. Plots of real (a) and imaginary (b) S11 parameters obtained from 3D simulations of muscle, fat, and side-by-side 50% fat and 50% muscle tissue samples. The S11 parameters from the fat/muscle interface tissue are compared with the S11 values calculated by averaging the muscle and fat S11 parameters.

![Graph of relative permittivity](image3)

Fig. 8. Relative permittivity obtained from 3D simulations of muscle, fat, and side-by-side 50% fat and 50% muscle tissue samples. The relative permittivity values of the fat/muscle interface tissue match the relative permittivity values calculated by averaging the muscle and fat relative permittivity.

Concentric tissue arrangement

From measurements performed on concentrically heterogeneous samples (an example of concentrically
heterogeneous region was provided in Fig. 4, on the right), permittivity data close to that of the inner tissue was obtained. In Fig. 9, the average relative permittivity measured from fat tissue, muscle tissue, and the two concentrically heterogeneous regions, one with fat in & muscle out and the other one with muscle in & fat out are shown. In the plot, it can be observed that the permittivity values obtained from regions with muscle in & fat out are within 15% from the permittivity values obtained from muscle tissue. Conversely, the permittivity values obtained from regions with fat in & muscle out are within 10% from the permittivity values obtained from fat tissue. This comparison suggests that the inner tissue may have a dominant impact on the measured dielectric data.

In order to confirm the measurement outcome, the simulation results from the two concentric samples consisting of 50% fat and 50% muscle described in Section III.B were compared with the simulation results from homogeneous muscle and fat samples. The results from simulations with only fat, only muscle, 50% muscle in & 50% fat out, and 50% fat in & 50% muscle out, are plotted in Fig. 10, in terms of S11 parameters, and in Fig. 11, in terms of relative permittivity.

From both the real and imaginary S11 plots of Fig. 10, it is clear that the results obtained from the simulated heterogeneous samples (one with 50% muscle in & 50% fat out and the other one with 50% fat in & 50% muscle out) are considerably different between each other and do not match the S11 values calculated by averaging the fat and muscle S11 parameters. Specifically, from the real S11 plot, an average difference of 30% is observed between the traces of the 50% muscle in & 50% fat out sample and muscle, and an average difference of 3% is observed between the traces of the 50% fat in & 50% muscle out sample and fat. Conversely, from the S11 imaginary plot, an average difference of 8% is observed between both the heterogeneous samples and the corresponding homogeneous ones. This comparison confirms the outcome regarding the dominant impact of the inner tissue on the acquired signal. Furthermore, all the S11 traces in Fig. 10 are from 2D axis-symmetric simulations and show a systematic noise component, which is not present in the S11 traces from 3D simulations in Fig. 7. The systematic noise in the S11 traces in Fig. 10 can be attributed to mesh and solver configuration differences between 2D and 3D simulations. However, except for the systematic noise, the fat and muscle traces in Fig. 10 illustrate trends equivalent to the fat and muscle traces in Fig. 7, thus demonstrating consistency between 2D and 3D simulation results. Additionally, the systematic noise of the S11 traces in Fig. 10 does not impact the relative permittivity traces in Fig. 11 obtained from the conversion of the corresponding S11 parameters.

As is clear in Fig. 11, the relative permittivity from the simulated 50% fat and 50% muscle tissue concentric samples are significantly different from the relative permittivity values calculated by averaging the simulated muscle and fat permittivity. Specifically, an average relative permittivity difference of 33% was found between the calculated mean relative permittivity and the relative permittivity from the sample composed of 50% muscle in & 50% fat out. Furthermore, an average permittivity difference of 55% was found between the calculated mean relative permittivity and the relative permittivity from the sample composed of 50% fat in & 50% muscle out. These relative permittivity differences, as with the differences in the real S11, suggest that the inner tissue has a higher impact (than the outer tissue) on the acquired permittivity, especially if the inner tissue has lower permittivity.

Fig. 9. Average relative permittivity calculated across five measurements on muscle, fat, and concentric fat and muscle tissue regions, which consisted of inner muscle/fat tissue having radii ranging from 0.5 to 0.9 mm surrounded by fat/muscle tissue.

Fig. 10. Plots of real (a) and imaginary (b) S11 parameters obtained from 2D simulations of muscle, fat, and two 50% muscle and 50% fat tissue concentric samples, one with fat in & muscle out, and the other one with muscle in & fat out. The S11 parameters from the heterogeneous tissue samples are compared with the S11 values calculated by averaging the muscle and fat S11 parameters.
Notably, these results are substantially different from those obtained in the previous section with samples consisting of side-by-side 50% fat and 50% muscle tissues (and shown in Fig. 8), in which fat and muscle tissues contributed equally to the acquired permittivity.

Although the general outcome regarding the dependence of the sensing radius and tissue contribution on the tissue sample structure and composition can be extended to any type of probe, the quantitative findings obtained for the slim form probe cannot be generalised to other probes. In fact, the sensing radius significantly depends on the probe design, i.e., the size of the inner conductor, the insulator, and the outer conductor, and on the fabrication materials.

Further experiments involving more tissues covering different ranges of dielectric properties are needed to further define the sensing radius across a wide range of measurement scenarios. However, overall, this study has provided the foundation for more accurate dielectric measurements of heterogeneous tissues, and will support the development of effective EM medical devices.

V. CONCLUSION

The sensing volume of a dielectric probe is a key parameter that enables accurate interpretation of dielectric measurements of heterogeneous biological tissues. In this work, the sensing radius of a coaxial probe was quantitatively investigated, and both measurements and simulations were performed to examine how different distributions of tissues within the sensing volume contribute to dielectric measurements. It was confirmed that the sensing radius depends on the dielectric properties of the tissues within the sensing volume. Furthermore, the sensing radius can be smaller than the radius of the probe; in fact, it was found to be, at most, 1 mm. Lastly, it was demonstrated that tissue distribution within the sensing volume greatly impacts how the tissues contribute to the dielectric measurement: side-by-side tissues contribute equally; while in concentrically arranged tissues, the inner tissue contributes dominantly, especially if it has low permittivity.

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