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Comparison of in-vivo and ex-vivo Dielectric Properties of Biological Tissues

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Abstract —

Accurate knowledge of the dielectric properties of biological tissues are crucial for various applications such as assessment of specific absorption rate and safety of electromagnetic medical devices. Most of the availably dielectric data in literature is based on *ex-vivo* measurements on biological tissue samples obtained from various animal models. This study investigates the differences in the *in-vivo* and *ex-vivo* dielectric properties of biological tissues, and variance over several animal species. The dielectric data is obtained from literature and organized to a unified format for comparison. The analysis shows considerable variations not only between *in-vivo* and *ex-vivo* dielectric properties of various tissues but also between various animal species.

1 INTRODUCTION

The dielectric properties of biological tissues have been widely studied at microwave and radio frequencies since the early 1950s [1–3]. These properties, namely, the conductivity and relative permittivity, determine the response of a material to an applied electromagnetic field [4]. The complex permittivity ε of a material is frequency dependent and is defined as:

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \tag{1}$$

where $j = \sqrt{-1}$, ω is the angular frequency, $\varepsilon'(\omega)$ is the relative permittivity (also called dielectric constant) and $\varepsilon''(\omega)$ is the dielectric loss. The relative permittivity reflects the material's ability to store energy and the loss factor represents the energy dissipated in the material. The dielectric loss can be converted into effective conductivity using:

$$\sigma(\omega) = \omega\varepsilon_0\varepsilon''(\omega) \tag{2}$$

where ε_0 is the permittivity of free space.

The precise knowledge of dielectric properties of biological tissues is essential for a wide variety of applications such as determination of Specific Absorption Rate (SAR) and evaluation of possible health hazards associated with non-ionising radiation, design and evaluation of electromagnetic diagnostic and therapeutic medical devices including microwave imaging and ablation [5–9].

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A number of studies have reported *in-vivo* and *ex-vivo* dielectric properties of several biological tissues of human and animals over a wide frequency range of 10Hz to 40 GHz, using various measurement techniques. One of the largest and most comprehensive studies of the *ex-vivo* dielectric properties of human tissues was performed by Gabriel *et al.* over a wide frequency range of 10Hz to 20 GHz [10–12]. Other *ex-vivo* dielectric studies in past few decades for human and animal tissues includes [9, 13–19]. The literature on *in-vivo* dielectric properties of human and animal tissues includes [13, 14, 16, 20–23].

The available data in literature is in the form of either a graph, a table, or a mathematical parametric model that makes it difficult to collate and compare. In particularly, there is limited data available in microwave frequency range and above. Such frequencies are important for potential medical applications and human safety concerns [6–8, 24]. Furthermore, there are conflicting views about the difference between the dielectric properties of *in-vivo* and *ex-vivo* tissues. Early studies suggest that there is a significant contrast between the *in-vivo* and *ex-vivo* dielectric properties of different biological tissues [9, 25]. The differences observed in relative permittivity were more prominent at lower frequencies, while the variation in conductivity values was high over the entire frequency spectrum. However, most recent studies have suggested that the contrast between *in-vivo* and *ex-vivo* dielectric properties is not significant provided that the environmental conditions and other physiological factors remain fixed [23, 26]. Recently, L. Farrugia *et al.* [23] performed *in-vivo* and *ex-vivo* dielectric measurements on rat liver tissue and concluded that temperature and dehydration are the major contributors to the difference between *ex-vivo* and *in-vivo* measurements. The uncertainty in the true dielectric properties of biological tissues can have a significant impact especially on microwave imaging and applications.

The purpose of this study is to: 1) collect and organize the available dielectric data on wide range of biological tissues from literature; 2) quantify the difference between in-vivo and ex-vivo dielectric properties of different tissues; and 3) quantify the difference between dielectric properties of tissues from different species. In this study, the dielectric data only within microwave frequency range is considered, where most of the data is in range from 100 MHz to 40 GHz. It was not feasible to analyse the data for all the tissues in this paper. Therefore, four most widely studied tissues are selected from available data in literature for comparison.

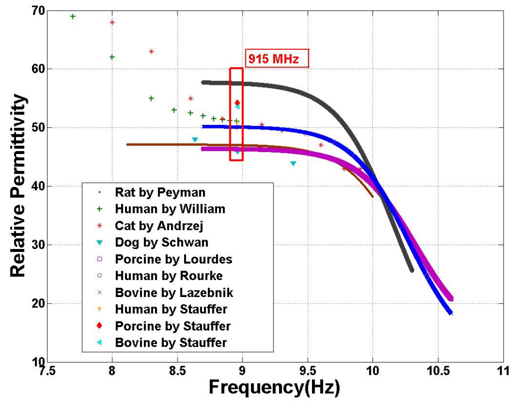
2 Data Collection

The *in-vivo* and *ex-vivo* dielectric data of human and animal tissues was collected from literature over the frequency range of 100 MHz to 40 GHz. The temperature of the tissue samples in these studies varied from 20^oC to 38^oC. The dielectric data in literature is available in the form of graphs, tables, or dielectric models. To avoid any interpretation error, the data in graphical form was not included in the analysis. The data in tabular form was available for discrete frequencies and in some cases only one to two frequency points (915 MHz and 2.45 GHz). In contrast, dielectric models are valid for a wide frequency band, and dielectric properties can be inferred from these models for any frequency point within the band. In order to include maximum possible data, the comparison has been made against most common frequency points in the available data. The data was also translated to relative permittivity and conductivity expressed in S/m from various forms available in literature.

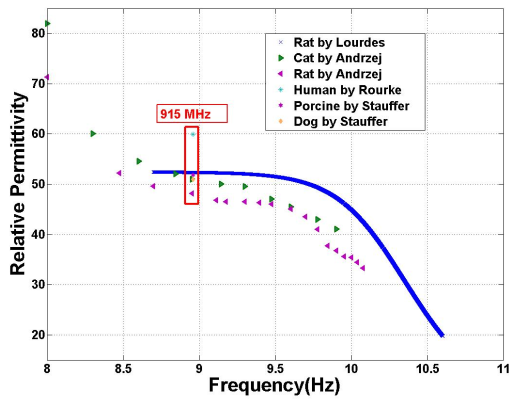
3 Results and Discussion

Fig. 1 (a) and (b) show *ex-vivo* and *in-vivo* dielectric properties of liver tissue for six different species, respectively. The data presented by solid lines was inferred from dielectric models while rest is the measured dielectric properties from different studies. Considering the diversity in available data, most common frequency point (915 MHz) is selected for comparison. It is also approved frequency for ablative therapy. The rectangular boxes in Fig. 1 highlight a significant variation in the available data. The overall variations in *ex-vivo* and *in-vivo* dielectric properties of tissues are 25.1% and %24.36, respectively. The variation in conductivity for both *ex-vivo* and *in-vivo* data is 35% and 25%.

Fig. 2 shows the comparison of *ex-vivo* and *in-vivo* dielectric properties of five different tissues at 915 MHz from bovine, ovine, porcine, rat, dog, cat and frog. Each box plot in the graph represents the dielectric properties of single tissue from different species. The single line in the figure represents that only one data sample is available. There is more than 10% variation between species for all tissues especially for kidney, spleen and brain. There is a relatively large variation in conductivity, particularly in the case of spleen and kidney. The variation in all cases is more than the reported uncertainty of the measurement system, which can be either due to natural heterogeneity of tissue or inter-specie difference. Moreover, it is clear that even at single frequency point, the available data may not be representative of actual *in-vivo* dielectric properties of biological tissue.



(a) Relative permittivity *ex-vivo* liver tissue

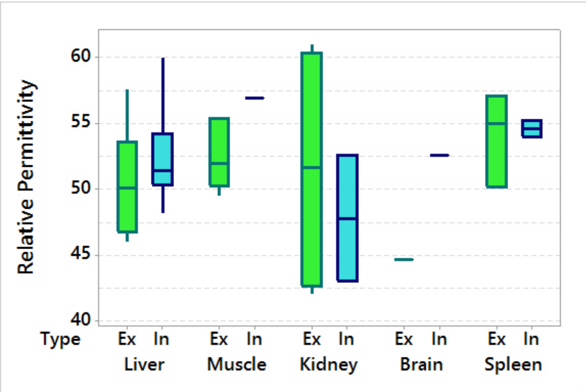


(b) Relative permittivity *in-vivo* liver tissue

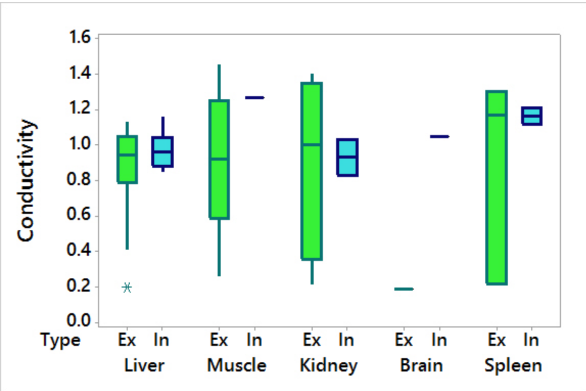
Figure 1: Comparison of *ex-vivo* and *in-vivo* dielectric properties of liver tissue.

4 Conclusion

In this study, the available dielectric data on wide range of biological tissues from literature was collected and organized. For analysis, the dielectric data within microwave frequency range was considered, where most of the data is in range from 100 MHz to 40 GHz. In this paper, a comparison of *in-vivo* and *ex-vivo* dielectric properties of



(a) Relative permittivity *ex-vivo* vs *in-vivo* for five different tissues



(b) Conductivity *ex-vivo* vs *in-vivo* for five different tissues

Figure 2: Inter-species comparison of *ex-vivo* and *in-vivo* dielectric properties of five different tissues at 915 MHz.

biological tissues has been presented. The results demonstrate a considerable variation up to 25% for permittivity and 30% for conductivity between *ex-vivo* and *in-vivo* dielectric properties of selected tissues. The results also demonstrate more than 25% variation between the dielectric properties of same tissue for different species. For microwave imaging and diagnostic device development, a slight error in the dielectric properties can have significant effect on the accuracy and reliability of the device. Moreover, the results suggest that the dielectric properties of tissues from an animal specie may not be applicable to other species, and a generalization of the data may not be valid. Further investigation is required to understand and characterize the variance between species.

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