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(Article begins on next page)

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Standardising Dielectric Property Measurements of Biological Tissues: An Overview on Open Ended Coaxial Probe and Measurement Guidelines

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***Abstract*—The dielectric properties of biological tissues dictate the interaction of electromagnetic waves with the human body and are therefore essential for the design and optimisation of electromagnetic-based medical technologies. Several methods are available to obtain these properties; the open-ended coaxial probe method is the commonly employed. Although such measurements have been performed for more than two decades, there is no clear consensus within the community regarding the accompanying metadata. In recent years, best-practice guidelines for conducting these measurements have been proposed, yet their adoption remains limited. In this review, we revisit the existing guidelines for measuring dielectric properties of biological tissues, including recommended practices and metadata requirements. Furthermore, we propose and provide a practical, implementable table aligned with the proposed best practices, with the aim of promoting standardisation and enhancing comparability across studies.**

Index Terms*—dielectric properties, biological tissues, standardisation, guidelines.

I. Introduction

The dielectric properties of biological tissues, namely, relative permittivity and conductivity, determine the interaction of the electromagnetic (EM) field with the human body [1]. The study of these properties is essential for the design and use of EM medical technologies such as microwave imaging, microwave ablation, and microwave hyperthermia [2] – [4]. These diagnostic and therapeutic modalities have gained significant attention in recent years due to their non-invasive and non-ionising nature [5].

Since these technologies exploit the dispersive dielectric nature of biological tissues and the contrast between healthy and diseased tissue, accurate characterisation of tissue dielectric properties is critical for the continued advancement of EM medical technologies. In this respect, one of the pioneering studies was performed by Gabriel et al. [6]. The authors measured the dielectric properties of several biological tissues from 10 Hz to 20 GHz using three different acquisition equipment and open-ended coaxial probes (OECPs) [6]. The tissues properties data collected from this study and existing literature sources [1] were combined to form a comprehensive dataset spanning 10 Hz – 100 GHz. The four-pole Cole-Cole model was then used to model the frequency dependence of the dielectric properties in the band of 10 Hz – 100 GHz [7]. This model is considered a benchmark database for the dielectric properties of biological tissues, useful for studying the interaction of EM field with the human body. Although the model provides the best estimate based on the experimental data, for lower frequencies the literature values are scarce and have larger than average uncertainties [7].

With the advancement of EM-based medical technologies and the efforts to improve the precision of treatment and diagnosis, the demand for an extended catalogue of dielectric properties of various healthy and diseased tissues has substantially grown. To meet this need, several studies have been conducted to characterise biological tissues [8] – [11], mainly using the OECP. While alternative methods such as the transmission line and waveguide, impedance-based, and resonant cavity techniques exist, they are less frequently employed in practice. In the absence of common reporting standards, the reporting of experimental metadata and measurement protocols is often incomplete, hindering the reproduction, and reusability of the data [12]. Consequently, Porter et al. [12] proposed a minimum information framework called MINDER regarding the metadata that should be reported along with the measured dielectric data. Additionally, Farrugia et al. [13] presented practical guidelines for the measurement of dielectric properties of biological tissues using an OECP setup, reinforcing the importance of comprehensive metadata reporting. Collectively, these two studies highlight the importance of best practices to ensure efficient and useful set of measurements which have been adopted in later studies.

This work revisits the guidelines in the literature to measure the dielectric properties of biological tissues, using the open-ended coaxial probe method. It further emphasises the need to report metadata aligning with FAIR (findability, accessibility, interoperability, and reusability) [14] principles of data management to ensure the reproducibility and reusability of data. Finally, with the goal of promoting community adoption of the current best-practice guidelines a practical and implementable laboratory data reporting form

was developed based on best-practice guidelines suggested by the MINDER framework [12] and Farrugia et al. [13] to be used during dielectric measurements for reporting the metadata.

II. Open-Ended Coaxial Probe

The OECP consists of a terminated section of transmission line, which guides EM waves from the source along the coaxial line toward the termination [5]. When there is a mismatch in the EM properties of the line, due to the interface between the line itself and the material under test (MUT), part of the wave is reflected towards the source [15]. Greater contrast in their EM properties leads to stronger reflections. The corresponding measurement set-up, together with a cross-section of a typical OECP, is shown in Fig. 1a. For liquids, the probe is immersed in the sample, whereas for solids, powders, or biological tissues, the probe touches the surface of the material. In this configuration, a Vector Network Analyser (VNA) is used to measure the reflection coefficient over a frequency range, and the collected data is then converted into complex permittivity values via modal expansion, quasi static approaches, or lumped-circuit models [16], [17]. There are several commercially available OECPs for material characterisation, some including in-built dedicated software to calculate the complex permittivity from measured reflection coefficients, while others depend on external software. Commonly, information of the algorithms used to derive the complex permittivity is limited or unavailable. Nevertheless, open-access algorithms have been developed [18] that can be used with different VNAs and commercial probes.

The open-ended coaxial probe is ideal for the characterisation of liquids, but it has also demonstrated adequate results in the characterisation of semi-solid materials, such as biological tissues, becoming the most commonly used technique in this field [5] – [11], [15], [18] – [22]. Some of the reasons include its practical and operational simplicity, as it allows for direct, and rapid measurements without complex experimental setups; the sample preparation is not difficult and non-destructive; it can be used in a broad frequency range for both *ex vivo* [8] – [11], [21], [22] and *in vivo* samples [20]. Moreover, as illustrated in Fig. 1b, the direct interaction between the probe tip and the MUT's EM field improves measurement reliability by reducing the impact of external EM interference.

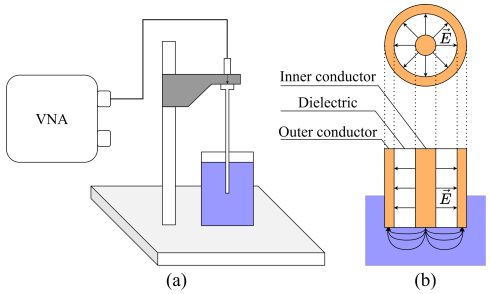


Fig. 1. Open-ended coaxial probe technique: (a) Measurement set-up; (b) cross-sections of the coaxial probe.

Although the advantages of the OECP, achieving accurate and repeatable measurements in biological tissues is complex [13]. The variability in dielectric data arises mainly from tissue heterogeneity, experimental confounders, and calibration standards, as well as random factors that could introduce errors during and post-measurement stages. Therefore, it is important to establish best-practice guidelines for the dielectric characterisation of biological tissues to provide consistent, accurate, and reproducible results. This includes, among others, reporting hardware setup, measurement configurations, and tissue preparation methods. The following section outlines the measurement process with the OECP, emphasising best practices to improve accuracy and consistency.

III. Measurement Procedure and Conditions

The measurement process involves multiple steps, each of which could introduce potential systematic, procedural, and post-measurement errors that compromise data accuracy and reliability when best-practice guidelines are not followed. Each of these factors are discussed below:

A. System/equipment set-up

The measurement protocol starts with the system mechanical set-up, ensuring it remains stable and free of vibrations before any calibration or measurement. Environmental factors such as temperature, pressure, and humidity can influence measurement outcomes and need to be documented along with the data [5], [12], [13]. For instance, temperature significantly impacts the permittivity of water in biological tissues, while pressure alters tissue density and water content, compromising measurement accuracy. Moreover, secure connections between the VNA and the OECP are also required. Furthermore, it is important to respect the manufacturer's recommended warm-up duration for the VNA before any measurement stage [23], [24]. Additionally, VNA settings such as frequency range, frequency sweep format, number of points, averaging, intermediate frequency (IF) bandwidth, and output power are fixed according to the measurement purpose.

B. Calibration

After setting up the system, a calibration stage is required before measuring the MUT. The probe must be properly calibrated to compensate for system related errors. Moreover, calibration directly affects the accuracy of the measured reflection coefficient; any error introduced during calibration propagates to the complex permittivity values. Calibration of one-port system such as the OECP, involves measuring three well known standards: open-circuit, short-circuit, and load. The open-circuit typically involves leaving the probe aperture open, while the short circuit can involve metal plates, specialised jigs, or soft materials covered in metal foil pressed to the probe tip. The load standard is commonly a liquid such as ethanol, deionised water, or NaCl solutions [5], [13]. Differences in calibration protocols, such as the choice

of reference standards and procedures, are the major source of variability between studies. As a result, comparing datasets directly is not straightforward because discrepancies may arise from sample or calibration biases. Good measurements of the standards compensate for systematic errors of the system, but not for random sources of errors or noise. When calibration is completed, the time should be recorded to evaluate possible drift errors and decide on whether re-calibration is needed. Additionally, any perturbation, or alteration of the set-up should be avoided after this point to minimise post-measurement errors.

C. Measurement validation

Following calibration, the next step corresponds to its validation. At that stage, other material(s) different from the load standard and MUT, with well-known dielectric properties, can be used as validation material. Variances in relative permittivity and conductivity up to 5% are acceptable at few Gigahertz. This validation process should be routinely conducted during tissue measurements to ensure accuracy over all measurements. Moreover, if the variance is higher than 5%, a new calibration should be performed [13].

D. MUT measurements

Once the measurement system is calibrated, the tissue sample, already prepared with adequate size, thickness, and preserved hydration, should be placed in a holder, and the probe should guarantee good contact with the tissues, adequate pressure [19], [22], and stability. Adequate size and thickness ensure adequate cover of the probe sensing area to prevent edge effects and fringing fields [25]. For both homogeneous and heterogeneous samples, multiple independent measurements should be taken at different points distributed in the sample volume, and the results should be averaged. For reliability, at least three independent measurements should be performed at each location [13], with the probe carefully cleaned between trials using water followed by alcohol for disinfection. In addition to measurements, the sample temperature and environmental variables should also be reported [12], [13].

E. Data post-processing

The following steps after measurements include data post-processing. For broad bandwidth measurements, Kramers-Kronig (KK) relations can be used to detect experimental outliers [13]. Moreover, uncertainty analysis is also recommended, and the method for calculating uncertainty should be documented with the results. Further details and guidelines for correct uncertainty analysis are provided in [26], [27]. Multiple independent measurements of the same tissue help quantify measurement repeatability, while systematic uncertainty components must be evaluated separately through calibration analysis and methods described in [26], [27].

F. Data analysis

Final measurement protocol steps involve analysing data. Typically, dielectric values are fitted to models like Debye or Cole-Cole to obtain closed-form expressions. It is important to report the number of poles, fitting errors, and parameters of the models. This guarantees data can be re-used and integrated into simulations if needed [13]. Data analysis also includes comparing these dielectric values with existing literature and performing statistical analysis.

Each step in the measurement procedure described above faces unique confounders, introducing measurement errors. A detailed analysis of these confounders and metadata that may be collected at each stage is discussed in the following sections.

IV. Confounding factors

Confounders are defined here as factors that affect the measured dielectric properties independently of the intended cause, namely, the intrinsic tissue properties. They are likely the source of inconsistency in the dielectric characterisation of biological tissues [12], [5]. If not accounted for, they can systematically bias measurements, hinder reproducibility, and compromise the comparability of data across studies [12].

A multitude of factors have been identified that can be broadly categorised into three groups:

- **Equipment- or system-related**, such as frequency used, calibration procedure, calibration drift over time, validation procedure, choice of reference liquids, disconnection or movement of cables. Even subtle cable displacements or imperfect connections can affect the reflection coefficient, highlighting the need for mechanically stable probe–cable–VNA configurations and sufficient instrument warm-up periods to ensure reliable calibration and measurements [28], [10].
- **Tissue- or clinical-related**, including tissue source, sample size, sample handling procedures, probe–tissue contact and pressure [28], hydration state, blood flow, time since excision, anaesthesia or drug effects, tissue heterogeneity, histological analysis [7], [10].
- **Modelling- or analysis-related**, arising from the choice of dielectric model, the number of poles used, and the accuracy of the employed fitting algorithm [28], [11].

Several confounders have been thoroughly investigated and can be mitigated through good measurement practice. For instance, equipment-related issues such as calibration drift can be reduced by employing a standard three-step calibration procedure when the accuracy is noted to be decreasing. At the same time, the selection of probe type is another design decision that can introduce variability, since sensing depth, frequency range, and manufacturer specifications limit which biological samples can be reliably assessed. Cable movement artefacts can be minimised using fixed probe setups, such as using an elbow connector with the probe directly connected to the VNA.

Tissue temperature, a critical variable, can be stabilised with controlled measurement environments by using a

temperature-controlled container, and hydration loss can be slowed through appropriate sample handling protocols, such as by minimising the time between excision and measurement for *ex vivo* measurements [5]. Room temperature, humidity, and pressure can also influence both instrument performance and tissue dielectric properties and should be monitored or controlled whenever possible [13].

Despite advances in methodology, certain confounding factors remain difficult to account for. Probe–tissue interface effects, arising from air gaps, surface irregularities, inconsistent contact pressure, or the presence of biological fluids such as blood within the sensing volume, continue to compromise measurement accuracy. Such effects are best addressed through careful visual inspection of the probe, regular cleaning to prevent contamination, and controlled probe–tissue contact procedures. Other factors remain open challenges for which no consensus solution exists, notably the characterisation of highly heterogeneous tissues. In such cases, the measurement obtained with an OECP reflects an averaged response across the sensing volume, meaning that a measurement at a single site may not be representative of the entire tissue sample [13]. Other unresolved issues include the choice of calibration reference materials, the impact of *in vivo* versus *ex vivo* conditions, inter-species variability, and variability introduced by histological processing [29].

While many confounders can be reduced through established good practices, others persist as obstacles to reproducibility and standardisation.

V. Reporting: Metadata, Existing Standardised Guidelines And Recommendations

Confounding factors may be mitigated through the reporting of metadata, that is, contextual information accompanying the measured data which captures their influence. At present, no community-wide consensus exists on the specific types of metadata to be collected, yet their explicit documentation remains essential to ensure that reported dielectric properties are reproducible, reusable, and comparable across studies. According to the MINDER framework [12] and the best-practice guidelines proposed by Farrugia et al. [13], the metadata that should be reported can be categorised into the following domains:

- **Instrumentation and Measurement Setup** – specifications of the hardware, measurement type, and software employed.
- **Acquisition Parameters** – frequency ranges, number of frequency points, scale, and power settings.
- **Calibration and Validation** – reference materials and loads, including their temperature, and the timing of calibration and validation procedures.
- **Sample Information** – origin, dimensions, collection method, preservation and preparation protocols, and time of excision.
- **Measurement Conditions** – environmental factors such as room temperature.
- **Data Acquisition and Replication** – number of measurement points, repetitions per point, number of samples, and number of subjects.
- **Data Processing and Analysis** – filtering methods, fitted models, and calculations of accuracy and uncertainty.

According to FAIR principles, all data and important metadata should be published for re-use of others. Following this, Farrugia et al. proposed an open-access repository [30] for the dielectric and thermal properties of biological tissues. The aim of this repository is to compile dielectric and thermal data together with the associated metadata, overcoming limitations of existing databases, such as those of IT'IS [31] and Gabriel et al. [1], which either did not include metadata or reported it only in a limited form [31, 1].

Despite some recent studies reporting the minimum information specified by the MINDER framework, several do not make the data accessible, hindering the reusability of this important data [8], [9].

In response to these challenges, we have designed a practical and implementable table for use during measurement of dielectric properties of biological tissues, which is available for download in the resources page of [30]. The table was developed in accordance with best-practice guidelines suggested by the MINDER framework and Farrugia et al. [13]. Thus, the required metadata will be ready to be then published in the open-access repository presented by Farrugia et al. Our goal is to promote community adoption of the current best-practice guidelines and to encourage standardisation and comparability across studies building upon the guidelines that we consider to comprehensively address the requirements for accurate dielectric measurements. Recognising that the volume of information to be recorded may pose practical challenges, particularly in time-constrained scenarios such as *ex vivo* measurements immediately following tissue excision, we have highlighted the data that should be captured during the procedure itself, with the remainder being completed retrospectively.

VI. Conclusion

The dielectric characterisation of biological tissues plays a vital role in the design of non-invasive EM-based medical technologies. Due to multiple confounding factors affecting the accuracy of the dielectric measurements, the best practical guidelines presented in the literature should be followed to ensure the accuracy and reusability of the data. In this study, several sources of errors during the overall measurement procedure were identified which can reduce data accuracy. The study further highlighted the best measurement guidelines for the OECP technique. Adopting these practices will promote greater transparency, comparability, and reproducibility in dielectric tissue characterisation, while also supporting the development of comprehensive tissue repository.

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