Minimum Information for Dielectric Measurements of Biological Tissues (MINDER): A Framework for Repeatable and Reusable Data

Emily Porter[(1)], Alessandra la Gioia[(1)], Saqib Salahuddin[(1)], Stefan Decker[(2)], Atif Shahzad[(1)], M. Adnan Elahi[(1)], Martin O'Halloran[(1)], and Oya Beyan[(2)]

(1) Translational Medical Device Laboratory, 2nd Floor, Lambe Institute of Translational Research, National University of Ireland, Galway, Ireland
(2) RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany

Abstract:

The dielectric properties of biological tissues characterise the interaction of human tissues with electromagnetic (EM) fields. Accurate knowledge of the dielectric properties of tissues are vital in EM-based therapeutic and diagnostic techniques, and for assessing the safety of wireless devices. Despite the importance of these properties, the field has suffered from inconsistencies in reported data. The dielectric measurement process of tissues is known to be affected by both measurement confounders and clinical confounders; however, adequate metadata is often lacking in the literature. For this reason, this work proposes a standard, called Minimum Information for Dielectric Measurements of Biological Tissues (MINDER). In the MINDER model, the minimum types of raw data and metadata needed to interpret or replicate a dielectric study are identified and described. Alongside the minimum information model, a controlled vocabulary for metadata parameters is proposed. We also provide an example of this model applied to a dielectric measurement scenario on a biological tissue sample. The MINDER model enables reproducibility of measurements, ease of interpreting and re-using data, and comparison of data across studies. Further, this standard framework will support dielectric data databases, with data searchable through metadata parameters such as temperature, frequency range, tissue type, and tissue state.

1. Introduction and Motivation

The dielectric properties, namely, the relative permittivity (ε_r) and conductivity (σ), of biological tissues quantify the interaction of electromagnetic (EM) fields with the human body. Specifically, the relative permittivity is a measure of how energy is stored in the tissues, and the conductivity is a measure of how EM fields attenuate in the tissue. Together, these properties characterise how EM waves are reflected at, absorbed by, and transmitted through the body [1]. Knowledge of the dielectric properties of various tissues is vital to the field of dosimetry (safety studies, such as for wireless communication devices) [2], and for the implementation of EM-based medical technologies, such as microwave ablation [3], hyperthermia [4], and imaging [5]. For example, in hyperthermia treatment of cancerous tumours, the dielectric properties are used to focus radio or microwaves at the tumour location, and impact the heating of the tumour [4]. If there are inaccuracies in the dielectric properties, then a location other than that of the tumour may be heated, or the heating may be insufficient to destroy or damage the tumour. As a result, hyperthermia treatment becomes more effective with improved knowledge of the dielectric properties of tissues in the region. The dielectric properties similarly impact other EM medical technologies.

While the dielectric properties of biological tissues have been examined for decades [6], the majority of the studies have been limited in scope, resulting in a large number of works but few that

overlap in terms of the parameters of interest, for example the tissues studied, frequency range used, or tissue temperature when measurements were conducted. These varied studies have been incorporated into comprehensive dielectric repositories [7], [8] and over time have become the *de facto* standard for EM modelling and therefore EM medical device development. However, despite the importance of these properties, no standard measurement or reporting techniques exist. As a result, there has been considerable inconsistencies in dielectric data, especially for key tissues such as the breast. Significantly, recent large-scale studies have produced results in direct conflict with historical studies, clearly questioning the validity of existing repositories [9]-[13]. The uncertainty in our knowledge of the dielectric properties of these key tissues are a clear barrier to the optimisation of existing EM medical technologies and the development of novel techniques, since it is no longer evident if the proposed medical techniques are viable based on the dielectric data.

Although the process of conducting a dielectric measurement on a tissue sample appears to be straightforward, there are a multitude of confounders that can impact the measured data. These confounders are likely the source of inconsistencies in reported data. The main equipment-based measurement confounders that have been shown to affect the accuracy of dielectric data include: the calibration procedure; calibration drift; calibration refresh; the validation procedure; the reference liquid used for validation and accuracy of its model properties; and the disconnection, reconnection or movement of cables or probe [1], [9], [14]-[29]. Uncertainties in the dielectric data caused by these measurement confounders have been thoroughly investigated over the years and can now be reduced or eliminated by following good measurement practice as identified in the literature [29].

However, clinical confounders have been relatively uninvestigated to date and may introduce a significant level of additional uncertainty into the dielectric data [29]. While not an exhaustive list, clinical confounders that have been identified in the literature are: the tissue source; animal age and weight; the use of anaesthesia/drugs; physiological parameters (blood flow, blood oxygenation, blood pressure, heart rate, respiration rate); *in-vivo* vs *ex-vivo* measurements; time since death/excision; the sample temperature and cooling or warming of the sample; sample dehydration and blood loss; contamination or artificial drying of surface; quality of probe-sample contact; probe-sample pressure; the sensing depth and sample size; tissue sample heterogeneity; the technique for marking measurement location on the tissue sample; sample or data exclusion criteria; pathologist methodology; and the histological analysis technique [1], [6], [7], [9], [10], [12], [13], [15], [17]-[21], [24]-[46]. Confounders can also be introduced when the dielectric data is reported in the form of models, due to the model type selection; the number of poles used in the model; the fitting algorithm used to obtain the model parameters; and the accuracy of the fitting technique [18], [26], [32], [35], [42].

Clearly, the number of confounders involved in the dielectric measurement process and the lack of consistency in data reported in the literature provide a solid motivation for the definition of a minimum information model that includes all relevant metadata. Specifically, in order to obtain accurate data, and to be able to reliably use and trust data, researchers need to control or compensate for these confounders with recorded relevant metadata. Very few, if any, studies currently report on all types of metadata. Furthermore, modern researchers rarely investigate dielectric properties just for the sake of understanding of dielectric properties themselves. The users of dielectric properties of biological tissues are largely biomedical engineering communities and medical device developers, and generating dielectric data is a small part of what they do. Consequently, there would be a huge advantage to being able to obtain consistent data and share it across institutions and disciplines.

Minimum information models have been used with success in other biology-related disciplines, for example, in cardiac experimental electrophysiology (MICEE) [47], proteomics (MIAPE) [48], neuroscience (MINI) [49], and genomic investigations (MIBBI) [50]. The use of a similar type of reporting standard would greatly benefit the field of dielectric metrology for biological tissues. With these motivating factors, in this work, we develop and apply a novel minimum information model for dielectric measurements of biological tissues, called MINDER. This model describes what types of raw data and metadata should be recorded and made available to the research community for data interpretation and repeatability. It also encapsulates a format for how the data should be stored for inter-disciplinary use. MINDER has been developed to adhere to the ISA (Investigation-Study-Assay) framework with a rich description of metadata [51], and follows FAIR data principles to make the data Findable, Accessible, Interoperable, and Re-usable [52]. This minimum information model will be made available online, along with a data repository. This model enables searchable data based on metadata, for example one could search for all dielectric measurements recorded with a specific measurement technique, or at a given sample temperature. In this way, MINDER will enable sharing and re-use of data, promoting transparency and validation of studies, and will give a level of confidence in dielectric data that was not possible before.

In the next section, minimum information models are introduces and their benefits highlighted. In Section 3, dielectric property measurements are described, demonstrating the need for a minimum information model. Then, the MINDER model is overviewed. In Section 4, the MINDER specifications and controlled vocabulary are presented, followed by an example implementation of this model. Lastly, in Section 5, the utility of MINDER is discussed and the paper is concluded in Section 6.

2. Minimum Information Models

In this section, minimum information models (MIMs) and their use in reporting are discussed. First, an overview of minimum information models is provided along with a description of why they are beneficial in science domains. Then, a set of principles underpinning high-quality MIMs are described; specifically the ISA (Investigation-Study-Assay) framework is introduced, which provides a format for MIMs that facilitates data collection and storage in compliance with the standards; and the FAIR data principles, which promote data integration and re-use, are described. Lastly, the state-of-the-art in existing minimum information models for biological and biomedical sciences is presented.

2.1 Description and Advantages

Reproducibility of an experimental result is a fundamental principle of science. Today, the required technical information to allow experiments to be repeated are presented, usually briefly, in the Materials and Methods section of manuscripts [53]. However, most scientific protocols in the literature are poorly described and deficient in detail [54]. This insufficient capture of relevant protocol details hampers the reusability and repeatability of data, and adds inconvenience and cost through the need to duplicate and compare experiments. Furthermore, questions may arise regarding the true reproducibility of experimental data.

Minimum information checklists (or guidelines) have been introduced to tackle the reproducibility problem by standardising the reporting of experiments in an effort to improve the quality and reusability of reported data [55]. These minimum information models specify the background information required to fully understand the context, methods, data, and conclusions that pertain to a given experiment. Thus,

a minimum information model provides a set of standard guidelines for collecting and reporting data. The current diversity of experimental designs and analytical techniques complicates the discovery and evaluation of experimental data. Therefore, research communities increasingly favour that a regularised set of the available metadata ('data about the data') pertaining to an experiment be associated with the results, making explicit both the biological and methodological contexts [50].

MIMS are used both to describe data and the processes by which the data was created [56]. The main purpose of MIMs is to guide researchers in reporting their experiments, to facilitate sharing, validation and comparison of data. When a MIM is adhered to, it enables the resulting data to be easily interpreted, verified, and analysed by the rest of the research community. Having access to metadata related to the experiment, along with the collected data, allows researchers to repeat the study precisely, verify the outcomes, and base future studies on these results. Besides promoting transparency, MIMs support effective quality assessment. Furthermore, such models also serve as key 'use cases', in that they represent the distilled opinion of a particular community on the information that should normally be captured to effectively describe a given type of experiment [50]. Another benefit of using minimum information standards is an improvement in discoverability and reusability. Many type of data users may wish to integrate datasets from different sources. MIMs support and facilitate the development and inter-operability of databases or repositories of data, and thereby provide researchers the opportunity to re-use and share data, advancing the state of knowledge and reducing the need for wasted resource allocation on experiment duplication. MIMs, together with standard terminologies, enable the assembling of scattered datasets and harmonisation of the structure, formatting, and annotation of data, and thereby enable analysis and modelling [57].

MIMs generally focus on specific types of investigations or experiments, and are especially popular in cross-disciplinary fields such as experimental biology [47]-[49]. MIMs must be discipline-specific in order to provide appropriate, applicable reporting standards [47]. As discussed above, adherence to the MIM ensures that: i) metadata needed in interpretation of experimental data is collected; and ii) that the experiment is described in sufficient detail that it can be repeated accurately. In many fields, there may be multiple MIMs of interest, depending on the experiment that is being conducted. Data can be more effectively used across a large scale if related MIMs use the same formal naming schema for all parameters involved in a given field of research. MIMs are especially useful when implemented alongside ontologies, which provide formal definitions for all names, property fields, and the interrelationships between these properties. Overall, MIMs and ontologies are gaining popularity in a digital world where effective data usage is becoming a priority [58].

2.2 Underpinning Principles for MIMs

MIMs that are developed by specific communities in relative isolation risk being incompatible with each other, with each developing their own model for common elements of experiments. To avoid this isolation and duplication of experiments, the ISA framework may be used. The ISA (Investigation-Study-Assay) framework helps researchers to describe rich experimental metadata to ensure reproducibility and reusability. ISA framework and tools are designed to facilitate metadata reporting in compliance with a given standard [51]. In this framework, there are three categories of metadata that are built upon: "Investigation" details the context of the project, "Study" describes the research (i.e., the measurement techniques and processes), and "Assay" involves the analysis of data [51]. The ISA tool supports a rich metadata description of experimental parameters, such that resulting data and outcomes are repeatable and re-usable. In particular, the open-source ISA tools (available at [51]), allow researchers to: collect and

curate data in line with MIM standards; store data and submit it to public repositories; search for data already in repositories; analyse local data or shared data with existing tools; and obtain detailed information on experimental designs. The tools also enable publication of data along with the manuscript-based publications of studies. There are an ever increasing number of experimental or analytical investigations that are developed in line with the ISA framework. Notably, the ISA Commons [59] is a large community that uses this ISA framework to track metadata in order to support compliant collection, storage, and re-use of data in a vast range of fields of research.

Recently, a set of recommendations called FAIR Principles for scientific data management and stewardship were developed to foster optimal use of research data which is both human and machine searchable. FAIR data principles are a set of guidelines that describe how to make data **F**indable, **A**ccessible, **I**nteroperable, and **R**e-usable [52]. Managing data collection and curation in line with these guidelines facilitates innovation and research productivity, through integration of knowledge across researchers and institutions and re-use of data or results [58]. The ability of researchers to spread knowledge through data hinges on the ability to locate, gain access to, interpret, and integrate appropriate scientific data with their research interests. The FAIR principles support these goals.

Within each of the four elements of the FAIR data principles, there are several key points that should be addressed. In order for data to be findable, it must have features including: a unique persistent identifier (for both data and associated metadata) with searchable indexing; and rich metadata describing data in detail. Having findable data requires the use of metadata, and therefore all metadata types should be known and standards for their naming and definition followed. In order for data to be accessible, the data and metadata must be retrievable using the unique identifier through a universal, open procedure. Making data findable and accessible may involve using software tools to search for and access the data/metadata, and to define where the metadata, data, and related documentation is stored. For data to be interoperable, or re-usable by different types of researchers for different purposes, the data and metadata should use a formal, shared language for representing the data. This data format should adhere to standards for the relevant data types, and be compliant with any typical software applications. Finally, in order for data to be re-usable, the metadata should contain accurate and relevant property fields defined in line with existing standards [52], and should be made available with details on data usage restrictions and licenses.

2.3 Current State-of-the-Art

Minimum information models, such as reporting guidelines, standard terminologies, and standard formats, are increasingly being used in the structuring and curation of datasets. Such standards enable data sharing through various scientific communities [57]. In recent years, interest in open-access data and data sharing has also been increasing. Currently, it is not uncommon for scientific journals to require publication of data along with a manuscript, and funding agencies may require or promote open source data [47], [58]. As the ability to store and share large volumes of data digitally becomes a reality, formal reporting standards are vital to ensuring that data can be interpreted accurately and the results reproduced. Minimum information models provide the reporting guidelines for the minimum information through metadata and data, that should be reported about an investigation (whether carried out by measurement or simulation).

The application of minimum information models in the field of biology and biomedical techniques originated in 2001, with the Minimum Information About a Microarray Experiment (MIAME) guidelines

[60]. MIAME standards became the domain model for major data repositories and a requirement for publishing microarray-based transcriptomics experiments [60]. In the 16 years following publication, more than 4100 studies have cited this foundational minimum information model. Following the success of MIAME, minimum information standards were taken up by other scientific communities [47]-[50], [60]-[66].

However, to date no MIMs have been developed that describe dielectric measurements of biological tissues. The lack of such a reporting standard is contributing to inconsistency in both the resulting data, and in the types of metadata that are presented or published alongside the data. Differences in the types of metadata reported may be attributed to researchers considering some metadata to have a greater impact on interpretation of the resulting data than other types of metadata, and thus only the most vital metadata is discussed. Further, in recent years, researchers have identified sources of experimental or clinical confounders that impact dielectric data that were not previously known or discussed [27], [35], [46]. Despite the large volume of research in the field, questions still remain as to which confounders (i.e., which sets of metadata) impacting dielectric measurements of biological tissues are necessary for interpreting or repeating a dielectric study. Significantly, there are also no MIMs that are relevant or applicable to the electrical or dielectric measurement of tissues, or to the reporting of electromagnetic medical device investigations such as microwave imaging, microwave ablation, or microwave hyperthermia. Therefore, in the next section, the MINDER model is introduced and its features described.

3. Minimum Information for Dielectric Measurements of Biological Tissues

As discussed in the previous section, there currently exists no standards or minimum information models for dielectric measurements of biological tissues. As a minimum information standard could have significant positive impact on this field, we here introduce the MINDER (Minimum Information for Dielectric Measurements of Biological Tissues) model. The MINDER model is designed to be consistent with existing standards in the ISA Framework, and is in line with the FAIR data principles. The model encapsulates rich metadata for the dielectric measurement of biological tissues, and enables persistent identifiers for data enabling the development of searchable data repositories.

This model contains an explicit set of minimum information (data and metadata) that is needed to accurately reproduce or interpret a dielectric measurement of biological tissues. This model will support basic science dielectric researchers, as well as dielectric-data users such as the EM medical device community. We present this model in the hopes that such researchers will contribute to it, in terms of refining information deemed necessary, and we actively encourage them to do so.

We note that the MICEE model for cardiac electrophysiology experiments [47] has some features of similarity with our proposed MINDER model in that it describes a biomedical application with cross-disciplinary metadata from both biology and electrical engineering. The MICEE model includes key metadata that are involved in describing the tissue sample, many of which are also applicable to dielectric measurement studies. In this work, we have adapted these related portions of MICEE for use in the proposed MINDER model. However, in dielectric studies, the necessary metadata related to the experimental processes and procedures, data collection, and data analysis, vary significantly from those necessary in the MICEE cardiac electrophysiological investigations. Therefore, the development of a full minimum information model unique to dielectric studies was necessary.

While the main goal of MINDER at this stage is to specify the minimum information required for a dielectric property experiment of biological tissues, we are also proposing a standard nomenclature for the involved metadata parameters (see Section 4). With a controlled vocabulary and standardised nomenclature, the free-form entry of metadata is limited and a structured, more easily searchable representation of data is encouraged. In order to achieve this indexing of metadata, both the naming of each metadata parameter, and its corresponding definition, must be clear. Without such standardisation in metadata parameters, it would be difficult to compile data into a database, and data generated by various communities would be a challenge to search for and to use [60]. Therefore, a controlled vocabulary is necessary to maximise utility of the MINDER model.

In this section, first the dielectric measurement process and the different types of related metadata are described. Then, the MINDER model is introduced and its components detailed.

3.1 Dielectric Property Measurements of Biological Tissues

The dielectric properties of tissues are typically measured using an open-ended coaxial probe [9], [10], [14], [15], [18], [20], [21], [25], [41], [43], [45]. The probe technique is preferred over others (i.e., waveguide or transmission line methods) due to the ability to measure tissues in a non-destructive way with minimal sample handling. Use of the coaxial probe also enables *in-vivo* measurements, which are not possible with other techniques [1], [20].

A typical dielectric measurement set-up is shown in Fig. 1. A coaxial probe is connected directly to a vector network analyser (VNA), which records the reflection coefficient and converts it to complex permittivity. The VNA enables collection of broadband dielectric properties in one measurement sweep. Prior to performing measurements, the parameters of the data collection must be determined (i.e., frequency range, number of frequency points, etc.) [19]. Then, the measurement system (VNA and dielectric probe) must be calibrated. A three-load calibration, involving an open circuit, short circuit, and deionised water, is standard [18], [19]. The calibration procedure removes sources of systematic measurement error.

Following calibration, a validation of the measurement system is typically performed [18]. In order to validate that the calibration was successful, dielectric measurements of a sample with known material properties are recorded. Then, the recorded data can be compared to the properties of the known material and the accuracy of the measurement can be calculated. If the accuracy is satisfactory (the exact value is study-dependent and evaluated on a case-to-case basis), then the sample under investigation can be measured with the confidence that the measurement equipment is performing accurately.

In order to measure the sample of interest, it is placed in direct contact with the coaxial probe, applying an even pressure [19]. If the sample is a liquid, the probe is immersed into the liquid [19]. Then the data is recorded (typically automatically). Depending on the aim of the study, data may be taken from multiple measurement sites on a single sample, and/or from multiple samples. At the same time, the temperature of the sample(s) should be recorded. Other factors related to the measurement may be recorded as well, such as the pressure of the probe-sample contact [67], humidity [1], or physiological data if measurements are being performed on a live subject [1]. Best practice also requires another validation measurement of the known material at the end of the test measurements, in order to ensure that the accuracy of the measurement is still high [18].

After measurements are taken, a tissue sample may be preserved and processed for histological analysis [9], [10], [45], [46]. Histology enables identification of the tissue composition present within the sample, and its relative spatial distribution. Histological analysis is also used to confirm whether the tissue is healthy or diseased, and, if diseased, the type or grade of the disease [45]. At the same time, dielectric data analysis is conducted. The dielectric data may be fitted to numerical models for use in simulations and ease in reporting [42]. Common models include the Debye and the Cole-Cole models [38], [42], [45]. The model parameters are optimised to match the data using techniques such as the least-squares method or the genetic algorithm [68], [69]. An overview of the entire data collection process is provided in Fig. 2.

3.2 MINDER Overview

In keeping with the ISA framework, our MINDER model is divided into three main categories: 'Investigation', 'Study', and 'Assay'. As is typical, the Investigation section contains general high-level information related to the research project, including principal investigator of the study, researchers involved, study location, and study title. The Study section contains all elements related to the experimental design, including the materials under test, the environment of the experiment, and the study procedures. Lastly, the Assay section contains the actual recorded data of the experiment and related analysis information. A high-level schematic of the MINDER model is presented in Fig. 3.

The Study section aims to define the experimental scenario and methodology. Subheadings within Study are "Environment", "Material", and "Experiment". The inclusion of detailed descriptions of the experimental methodology is very important; it allows verifying the study outcomes, and enables a consistent protocol between studies. The key information to be included in the study is the equipment used, the materials measured, the environment of the experiment, the order and timing of the experiment components, and the sample storage/handling. Further, details on the number of measurement sites on each material sample and the location of these measurements are also included.

In the Assay section, there are two subheadings: Recordings and Analysis. The Recordings heading includes all dielectric measurement data. In particular, there are two subheadings: 'Validation Measurement' and 'MUT Measurement'. The validation measurements are used to confirm the quality of the calibration, and to calculate the measurement system uncertainty. The MUT dielectric property measurements are the output of interest of the study. The Analysis section includes parameters related to the investigation of the outputs of the measurement. The analysis section contains two key parts: 'Dielectric Analysis', and 'Sample Analysis'. The Dielectric Analysis examines: i) the uncertainty in the dielectric measurement, and ii) the fitting of the measured data to a numerical model that represents the data in a compact form. The Sample Analysis examines the histology of the measured sample, and its correspondence to the measured dielectric properties. This information enables tracking from the raw data to the final presented data, for instance that which is presented in journal papers.

In the next subsections, high-level descriptions of the Study and Assay categories are provided.

3.3 Study Details

In this section, the metadata falling under the 'Study' heading are detailed. These include: Environment, Experiment, Calibration, Material, Tissue Processing and Tissue Post-Processing. For each category of information, the types of information involved and the importance of them is discussed.

Experiment: This section details the measurement techniques, and software and equipment used in the study. A measurement device (typically a network analyser) is used to record the dielectric properties. Other measurement tools are also used to ensure reliability in the measurements, for instance a temperature probe to record the sample temperature, or a weigh scale to identify the pressure of the probe on the sample. Similarly, tools may be used to maintain a constant environment across measurements, for example a water bath or an environment-controlled atmosphere. In this section, all equipment types and their relative accuracies are detailed.

Calibration (Experiment): This section describes the manner in which the dielectric measurement equipment is calibrated. The goal of system calibration is to correct for any systematic errors in the dielectric measurement equipment (for example, mismatch in impedance at the connector:probe interface). Normally, calibration techniques use three materials of known dielectric properties. The materials (i.e., load types) used are to be indicated, along with their measurement temperatures. Measurement parameters are also generally set during the calibration phase and should be noted, including measurement frequency range, frequency scale format, and measurement power.

Environment: The information in this section relates to the environmental conditions under which the experiment is conducted. These conditions can impact dielectric property measurements and the lack of control or monitoring of conditions is a source of variation in measurement data. Environmental data is also useful for comparing dielectric property measurement results in a meaningful way. In this section, environmental factors include, for example, room temperature, and ambient pressure and humidity. This information allows for later study verification and emphasises the range of factors which can influence dielectric property measurements, encouraging data producers to collect relevant metadata during experiments.

Material: This section provides details on the material(s) under investigation. Depending on the nature of the dielectric study, the material(s) may be liquids, tissue-mimicking phantoms, or biological tissues from animals or humans. The materials under test should be listed and described. The sample size or liquid volume should also be provided. The source from which the material under test is derived or obtained must be detailed. For liquids, no 'source' is generally required. For phantoms, this section should include the constituent materials that make up the phantom. For animals or humans, the material may be an *in-vivo* tissue or an excised (*ex-vivo*) tissue sample sourced from the body. In this case, the animal type, animal characteristics (age, weight), and anatomical source (i.e., organ or region) should be provided. It can also be noted if the tissue was taken from a diseased organ or not, along with the type and grade of disease or condition. The tissue source is an important aspect in the measurement of dielectric properties of biological tissues, as measurement data may differ depending on whether the measurement was taken *in-vivo* or *ex-vivo*, and how long *ex-vivo*, as well as with physiological parameters.

Tissue Processing (Material): This section includes information about the tissue processing prior to, and up to the moment of, the dielectric measurement. It involves sample preparation and storage, such as method of animal dispatch and surgical procedures, storage and container conditions, handling, and preservation measures taken. Significant variation can be introduced into dielectric property measurements based on changes in the tissue handling procedures. In order to have repeatable measurements, the tissue procedures must be described to a high-level of detail so that they can be reproduced by others.

Tissue Post-Processing (Material): Tissue post-processing is required when the sample is to undergo histopathological analysis. The sample is typically subject to histopathology when the sample is of

unknown, or inhomogeneous, composition. For instance, histopathology may be used to determine if the tissue is diseased or healthy, or which proportion of tissue types make up the bulk tissue sample (e.g., fat, connective tissue, tumour, etc.). Generally, the process involves preservation and fixation of the sample, then embedding it in wax. Then, the sample is sliced thinly, stained, and images of each slice are taken. Finally, a pathologist examines the images to identify the tissue types present, and the type or extent of any disease present. While histology is regularly used in hospitals, variations in the procedure do exist and may affect the interpretation of the results. Thus, this section details the histological methods, including: tissue fixation media, slice thickness, stains used, and details of timing (how long after measurement the sample was placed in preservative, how long it was in preservative, etc.). This information promotes a correspondence between the measured dielectric properties and the tissue types that they have resulted from, as histology allows researchers to interpret the meaning of the dielectric data based on the tissue types that contributed to the dielectric measurement.

3.4 Assay Details

In this section, the data and metadata involved in the Assay category are detailed. First, the measurement recordings (both validation and MUT) should be saved in standard tab delimited 3-column format (i.e., first column: frequency points; second column: real part of the permittivity; third column: imaginary part of the permittivity). Then, analysis may be conducted. Depending on the study, the analysis may involve investigation of the sample or MUT, for example histologically, and it may include dielectric data analysis (for example, model fitting, error assessment, and comparison with literature data). Each heading within Assay is summarised in the following text.

Validation Measurement (Recordings): This section contains the recorded dielectric property measurements for each validation material. The data may be presented in standard array format (3 tab-delimited columns: frequency points; real part of permittivity; imaginary part of permittivity), or there may be a reference to the data location, depending on the access rights.

MUT (Material Under Test) Measurement (Recordings): This section contains the recorded dielectric property measurements for each material under test. As with the validation recordings, the data may be included, or there may be a reference to the data location, depending on the access rights.

Sample Analysis (Analysis): In this section, digital images of histology slides are under analysis. These images are used to determine the composition (in terms of tissue types) of the measured tissue sample. The method used to identify the tissue types should be noted, along with related measures (for example, the kappa score if multiple pathologists have examined the images). Further, the technique used to determine the tissue sample composition should be provided, and the method, if any, to correlate the dielectric properties with the histology slide. The resulting histological data may be included, or a reference to the data location provided.

Dielectric Analysis (Analysis): This heading contains subheadings of “Uncertainty Analysis” and “MUT Data Analysis”. In these sections, the analyses of the recorded dielectric properties of the validation material(s) and the samples are described. The heading “Uncertainty Analysis” includes information related to quantifying the measurement uncertainty of the system. This uncertainty is usually determined by comparing the recorded data from the validation material with a known model of the material in question. A reference to the known model should be reported here, along with the output of the comparison, i.e., the error between the validation recording and the known value. The type of error calculation used should

also be specified. Further, under the heading "MUT Data Analysis," the analysis relating to the dielectric data obtained from the sample is described. In general, measured dielectric properties are fitted to known models so that they can be integrated into numerical investigations more easily. In dielectric data analysis, information on the data post-processing is included: the criteria for excluding poor recordings, the type of model the data is fitted to and the number of poles, and the method for achieving the best fit. The error in the fit is also to be included.

4. Results

In this section, we present the MINDER model specifications, discuss definitions for the model properties, and overview the implemented controlled vocabulary. Lastly, we provide an example of the application of MINDER to a dielectric measurement of a bovine tissue sample.

4.1 MINDER Specifications and Controlled Vocabulary

In the MINDER vocabulary, each metadata parameter is given a unique name and is accompanied by a precise, clear definition. For each metadata parameter, or property, related to the investigation, the specifications include:

- **Property name:** unique metadata parameter name;
- **Related concept:** the relevant heading of the MINDER model that the property belongs to;
- **Expected type**: the format type of the property data (e.g., string, Boolean, integer, etc.);
- **Unit**: the measurement unit of the property, if relevant;
- **Description:** an explanation, or definition, of the property;
- **Cardinality:** the number of times in which a property can occur: *1* indicates a property may occur a maximum of once; *m* permits multiple instances.

Within a given property, as much as is possible, the expected type and unit of that property is from a controlled vocabulary list. However, some property fields are left free-form as a fixed set of options would be unlikely to adequately describe the diversity in studies at the current time (for example, in terms of the sample handling, due to the large number of potential handling procedures, and variations on individual procedures, across studies). Although space in this manuscript does not permit inclusion of the full MINDER specifications, a full list is provided in Appendix 1. Here, we highlight some of the key properties in Table I. In Table II, we provide a selection of the controlled vocabulary set for important properties. The controlled vocabulary for more basic properties (such as measurement units of frequency, volume, or size) is not discussed here.

4.2 Example of Tissue Dielectric Measurement with MINDER

Next, we present a sample dielectric measurement that we have conducted while simultaneously recording the relevant metadata. In this example measurement, we obtained a single bovine tissue sample from an abattoir, and performed a single dielectric measurement on the sample. The metadata for this investigation is summarised in Table III. Within the table, the data is subdivided by heading (as described in Section 3). The headings are presented in the order in which data is entered during an experiment. Any information not provided in the table, related to any of the headings, was not captured as a part of this study. As can be seen from the table, the amount of metadata involved in a dielectric measurement study of biological tissue is substantial. Further, it is important to note that this example

highlights a very basic investigation containing measurements on only one sample – if more tissue sources, samples, and measurement sites are involved, then the amount of metadata collected will increase.

In relation to this measurement example, the collected dielectric data is plotted in Fig. 4 for both the validation measurement and the MUT measurement. Also plotted in Fig. 4 is the model data for the validation material, and the Debye model calculated based on the MUT dielectric measurement. While graphical representation is not convenient for data usage and storage (data should be stored in text-based array format, as discussed in Section 3.4), it is used here to summarise the collected data in a concise manner.

5. Discussion

It is clear from the wide variation in measurement procedures and large number of confounders affecting dielectric measurements of biological tissues that a minimum information model to describe these measurements would be of great use in supporting interpretability and re-usability of such data. The MINDER model proposed here will satisfy these needs. The example in Table III demonstrates the utility of MINDER, linking metadata with multiple types of output data.

In accordance with a data management plan similar to the one described in [48], we suggest researchers conducting dielectric measurements on biological tissues in the following steps in order to achieve standardised metadata and data that are re-useable, searchable, and fully interpretable. First, the researcher should generate data and metadata as they typically would, and consider collecting additional metadata as specified in the MINDER model if applicable. Then, the data and metadata that is collected should be parsed according to the MINDER definitions, and saved in line with the controlled vocabulary standards. This information will facilitate accurate data collection, and incorporation of the data and metadata in online repositories.

In the coming months, the current MINDER model will be disseminated to the wider community of key stakeholders in the measurement and usage of dielectric data, including both research and industry members. Feedback from researchers in the community will be incorporated in order to provide a wide ranging set of minimum information metadata and data that is satisfactory for all experimental investigations of dielectric properties of biological tissues. Further, involvement from industry members, specifically those who provide dielectric measurement tools, will be very advantageous as many measurement tools are able to record select metadata along with dielectric data already and there is potential to record additional types of metadata automatically. The resulting, refined set of metadata will be consensus based, and will support the path to standardisation of dielectric data collection and reporting.

6. Conclusion

In this paper, we have presented a minimum information model for the dielectric measurement of biological tissues (called ‘MINDER’). There is a strong need for such a minimum information standard, as a dielectric measurement study contains a large number of often under-reported metadata, which has led to inconsistencies in data for key tissues and hinders our ability to interpret and re-use such data. The MINDER model is timely, as increasing research work is occurring in the field of electromagnetic medical technologies that rely on dielectric data of tissues, and the current emphasis on open data, and data sharing and re-usability. The MINDER model, and the corresponding controlled vocabulary, provide the

framework to improve this field through improved data reliability, transparency, repeatability, ease of data sharing and re-use, and encourage open-access data. While collection of relevant data initially adds work for researchers, it will be of long-term benefit to the community as a whole. Future work will examine ways to disseminate the model, and to train and encourage researchers in the field to take up use of this standard.

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Table I. Example of key MINDER specifications: including property names, types, and descriptions. Asterisks (*) indicate fields which correspond to a controlled vocabulary definition (i.e., the entering of information is not free-form but through selection of a limited number of options) and 'CN' indicates Cardinality (1 instance or m instances possible).

Property (Field Name)	Related Concept	Expected Type	Unit	Description	CN
Measurement technique	Experiment	String (*)	-	The type of technique used to perform the dielectric measurement.	1
Measurement Equipment	Experiment	String	-	The dielectric measurement equipment used (includes VNAs, probes, etc.)	1
Temperature measurement and control equipment	Experiment	String	-	Information on the thermometers or temperature probes used to measure material temperatures, and equipment used to control temperature (e.g. water bath).	m
Start frequency of measurement frequency range	Calibration	Integer	{Hz, MHz, kHz, GHz, THz} (*)	This field indicates the start point of the frequency range. Each calibration can correspond only to one frequency range.	1
Validation performed?	Validation	Boolean (*)	-	A validation measurement, or measurements, may be performed after system calibration to enable accuracy calculations. Each time validation is performed, a new validation instance is used. Each validation instance includes properties of the type of validation material, the validation material temperature, and the validation time.	m
Validation material	Validation	String (*)	-	If validation was performed, the type of validation material that was used.	1
Validation material temperature	Validation	Floating point	˚C, F (*)	If validation was performed, the temperature of the validation material.	1
Type of sample	Material	String (*)	-	Each individual measurement is conducted on a sample. The sample type can be standard liquid (ex: saline, alcohols), phantom (ex: TX151, oil-in-gelatin), or biological tissue (any tissue derived from human or animal sources).	1
Dielectric model type	Analysis	String (*)	-	The type of dielectric model used to model the raw data in closed form. Standardly used models are the Cole-Cole and Debye.	1

Table II. Controlled vocabulary set for key properties.

Related Property	Controlled Vocabulary Definition Set
Measurement technique	{open-ended coaxial probe; waveguide; cavity; transmission line; other}
Frequency scale format	{logarithmic; linear; custom}
Calibration liquid	{deionised water; other}
Validation material	{0.1 M NaCl; 0.9% NaCl; ethanol; methanol; ethanediol; deionised water; butanol; other}
Type of sample	{liquid; phantom; biological tissue}
Tissue state	{*ex-vivo*; *in-vivo*; *in-vitro; preserved*}
Tissue source species	{human; porcine; ovine; rat; mouse; bovine; dog; cat; other}
Tissue source organ	{lung, liver, muscle, kidney, heart, breast, skin, adrenal gland (cortex), adrenal gland (medulla), brain, white matter, grey matter, cortex, cerebellum, cornea, uterus, intestine, tumour, ovary, pancreas, stomach, testes, other}
Dielectric model type	{Debye; Cole-Cole; other}
Data to model fit optimisation method	{least squares method; particle swarm optimisation; weighted least squares method; hybrid particle swarm-least squares method; one-stage genetic algorithm; two-stage genetic algorithm, other}

Table III. Summary of metadata collected in line with the MINDER guidelines during a dielectric measurement study on *ex-vivo* bovine tissue.

Investigation	***Institution***	***Principal Investigator***	***Research Project name***	***Funding Sources***	***Researchers Involved***	***Experiment Title***	***Ethical Approval***	***Data Usage Rights***
	National University of Ireland Galway	Martin O'Halloran	BIOELECPRO	ERC	Emily Porter	Dielectric Measurement of Ex-vivo Heterogeneous Bovine Tissue	N/A	Unrestricted

Study – Experiment	***Measurement Technique***	***Measurement Equipment***	***Measurement Software***	***Temperature Measurement and Control Equipment***	***Accuracy for Temperature Measurement or Control equipment***	***Time of Equipment Turn on***
	Open-ended coaxial probe	Keysight E5063A and Keysight slim form 2.2mm diameter	Keysight Materials Measurement Suite	Hanna Checktemp1 EN13485 (for liquids); Precision Gold Infrared Thermometer N85FR (for tissue sample)	0.5 (for liquids); ±1% of reading (for tissue sample)	-48:00 (hh:mm)

Study – Calibration	***Start Frequency of Measurement Frequency Range***	***End Frequency of Measurement Frequency Range***	***IFBW***	***Power***	***# Frequency points***	***Frequency scale format***	***Calibration Time(s)***	***Calibration Liquid***	***Calibration Liquid Temperature***
	500 MHz	8.5 GHz	30 Hz	-5 dBm	101	log	00:00 min	Deionised water	22.1°C

Study – Environment	***Room Temperature***	***Humidity***	***Atmospheric Pressure***
	22.7°C	Unknown	Unknown

Assay – Validation Measurement	***Validation performed?***	***Validation material(s)***	***Validation Time(s)***	***Validation material temperature(s)***	***Validation material reference model***
	Yes	0.1M NaCl	00:01 min (pre-measurement); 00:12 min (post-measurement)	22.3°C (validation at 00:01); 22.2°C (validation at 00:12)	Peyman 2007 [70]

Study - Material	***Type of Sample***	***Tissue Source Species***	***Tissue source organ/region***	***Tissue state***	***Time since excision***	***Sample dimensions***	***Tissue handing procedure***
	Biological Tissue	Bovine	Unknown	Ex-vivo (excised)	Unknown	1.1 x 1.8 x 0.5 cm^3	Sample refrigerated then brought to room temperature. Tissue sectioned into smaller portions.

Assay – MUT Measurements	***Number of Measurement sites***	***Number of measurements at each site***	***Measurement time(s)***	***Number of averages for each measurement***	***Sample Temperature (at each measurement time)***
	1	1	00:03 min	1	22.4°C

Analysis – Uncertainty Analysis	***Error calculation type(s)***	***Calculated error***
	% difference, mean over frequency	1.69% (for validation at 00:01, pre-measurement) 2.47% (for validation at 00:12, post-measurement)
	% difference, mean over frequency, over all times	2.08% (over all times)

Analysis – MUT Data Analysis	***Dielectric model type(s)***	***Number(s) of model poles***	***Data to model fit optimisation method(s)***	***Exclusion criteria***	***Fitted Model parameters***	***Calculation method for error***	***Fitting error(s)***
	Debye	2	Weighted least-squares method (WLSM)	Kramers-Kronig based on model fit	ε_∞ = 8.537; σ = 0.190 (S/m); $\Delta\varepsilon_1$ = 6.118; $\Delta\varepsilon_2$ = 1.993; τ_1 = 1.281e-11 (s); τ_2 = 1.021e-10 (s)	Mean over frequency	0.66%

Appendix #1: MINDER Specifications Table

Property (Field Name)	Related Concept	Expected Type	Unit	Description	CN
Investigation Identifier	Investigation	string	-	Unique identifier for each research project. Investigation Identifier (format: 1stAuthorLastName_Publication/StudyYear_Publication/StudyMonth) Each investigation contains only one research project.	1
Research Project Title	Investigation	string	-	The name of the research project.	1
Research Project Description	Investigation	string	-	Descriptive information detailing the research project. Each project may contain multiple experiments.	1
Principal Investigator ORCID	Investigation	numeric	-	16-digit unique researcher identification number (https://orcid.org/) Format is XXXX-XXXX-XXXX-XXXX. One ID may be provided for each principal investigator.	m
Principal Investigator ID	Investigation	string	-	Unique ID for each principal investigator (format: LastName_FirstName_MiddleInitial) One ID may be provided for each principal investigator.	m
Principal Investigator Last Name	Investigation	string	-	The last name/surname of the principal investigator involved in carrying out the study. Must be listed for each principal investigator. Multiple principal investigators are possible.	m
Principal Investigator First Name	Investigation	string	-	The first name of the principal investigator involved in carrying out the study. Must be listed for each principal investigator.	m
Principal Investigator Middle Initial(s)	Investigation	string	-	The middle name initial(s) of the principal investigator involved in carrying out the study. May be listed for each principal investigator.	m
Principal Investigator Email	Investigation	string	-	Email address for principal investigator. May be listed for each principal investigator.	m
Principal Investigator Phone	Investigation	numeric	-	Phone number for principal investigator. May be listed for each principal investigator.	m
Principal Investigator Address	Investigation	string	-	Address for principal investigator. May be listed for each principal investigator.	m
Principal Investigator Affiliation	Investigation	string	-	Affiliation of principal investigator. Must be listed for each principal investigator.	m
Institution where study conducted	Investigation	string	-	The institution at which the investigation was carried out. Multiple institutions are possible.	m
Research Project Funding	Investigation	string	-	The funding sources of the research project.	m
Researchers Involved (including PI)	Investigation	string	-	List of researchers involved in the project.	m
Ethical approval	Investigation	boolean (*)	-	This field indicates whether ethics approval was obtained for the investigation. If no ethical approval was needed e.g. if no biological samples are used, “NA” for non applicable should be selected.	1
Data usage rights	Investigation	string	-	The usage rights for the data and metadata from the investigation should be specified here.	1
Experiment Identifier	Study	string	-	Unique identifier for the conducted experiment. There may be multiple experiments within each investigation.	m
Experiment Title	Study	string	-	Title of the experiment conducted. Each experiment has only one title.	1
Measurement Technique	Experiment	string (*)	-	The type of technique used to perform the dielectric measurement. (e.g., measurements may be coaxial-probe based, or transmission line based, etc.). Within each experiment, only one measurement technique is possible. However, an investigation may contain multiple experiments, each of which may use a different measurement technique.	1
Other Measurement Technique (If “Measurement Technique”=other)	Experiment	string	-	The type of measurement technique used, if not one of the listed options.	1

Measurement equipment	Experiment	string	-	The dielectric measurement equipment used, includes VNAs, probes, etc. Each experiment may have only one set of measurement equipment; however, within an investigation there may be multiple experiments each with different measurement equipment types.	1
Cable used to connect measurement equipment	Experiment	boolean (*)	-	This field indicates whether a cable was used to connect the measurement tool to the measurement recording equipment (e.g., probe to network analyzer).	1
Measurement software	Experiment	string	-	The dielectric measurement software that is used to obtain the dielectric properties from the S11 measurements. May be proprietary or custom. If custom, details should be provided regarding the software operation.	1
Temperature measurement and control equipment	Environment	string	-	Information on the thermometers or temperature probes used to measure material temperatures, and equipment used to control temperature (e.g. water bath). Multiple types of temperature measurement and control equipment may be used within an experiment. Each piece of equipment should be described individually.	m
Accuracy for each temperature measurement or control equipment	Environment	floating point	C, F, K, +/- % (*)	The measurement accuracy of this individual thermometer or temperature probe; or temperature control accuracy. It can be listed in C, F, K, or in +/-% of reading value. Each piece of temperature measurement or control equipment can have its own accuracy, and multiple accuracy values (of different accuracy types/formats) may be entered for each piece of equipment.	m
Room Temperature	Environment	floating point	C, F, K	Room temperature during the experiments.	1
Humidity	Environment	floating point	%	Relative humidity in the environment during the experiments.	1
Atmospheric Pressure	Environment	floating point	kPa, psi	Atmospheric pressure in the room where experiments are conducted.	1
Time of measurement equipment turn on	Calibration	floating point	h, min, s, less than (min), less than (h), more than (min), more than (h) (*)	This is the time of the measurement equipment turn on. Some types of equipment require a minimum amount of warm up time prior to measurements for accurate data. Note that a single time point, not a range, should be entered. Researchers may wish to define the measurement equipment turn on time as the 0:00 time of the experiment.	1
Calibration performed?	Calibration	boolean (*)	-	System calibration is typically performed prior to measurements. Each time calibration is performed, a new calibration instance is used. Each calibration instance includes properties of the type of calibration material, the calibration material temperature, and the calibration time.	m
Calibration Identifier	Calibration	string	-	Each calibration instance should have a unique identifier.	m
if(Calibration performed?=”yes”), Calibration liquid	Calibration	string (*)	-	This property indicates whether this individual calibration is performed on the standard deionised water or with another material. Generally, each calibration can be performed on only one load liquid (the other two calibration standards being open and short circuit). However, if calibration is performed using multiple load materials, they may each be described in the calibration section individually.	m
if(Calibration performed?=”yes”) && “calibration liquid” = “other”	calibration	string	-	If the calibration was not performed with deionised water, provide the calibration material here.	m
if(Calibration performed?=”yes”),	calibration	floating point	C, F, K (*)	This property indicates the temperature of the material used during this individual calibration.	m

Calibration liquid temperature					
if(Calibration performed?=”yes”), calibration time	calibration	floating point	h, min, s, less than (min), less than (h), more than (min), more than (h) (*)	This property indicates the time that this individual calibration instance was performed at. Note that a single time point, not a range, should be entered.	1
Number of frequency points	Calibration	positive integer	-	Each calibration can correspond only to one set of frequency points. In this field, the number of frequency points used in the calibration should be noted.	1
Frequency scale format	Calibration	string (*)	-	Each calibration can correspond only to one set of points. The frequency scale of the measured dielectric data. Should be provided for each measurement instance. The frequency points across the frequency range may be selected in linear or logarithmic fashion. Alternative selection of frequency points in the frequency range are possible – in this case ‘custom’ should be selected. If “Custom,” need to add more info in array format.	1
If {Scale of individual measurement}= “Custom”, the custom scale of the individual measurement	Calibration	array	Hz, kHz, MHz, GHz, THz (*)	The frequency points that make up the custom scale.	1
Measurement power	Calibration	floating point	dBm, mW (*)	The power of the signal from the network analyser for the given measurement.	1
Measurement Intermediate Frequency Bandwidth (IFBW) of individual measurement	Calibration	floating point	Hz, kHz, MHz, GHz, THz (*)	The IFBW of the recording from the network analyser for the given measurement	1
Start Frequency of Measurement Frequency Range	Calibration	positive Integer	Hz, kHz, MHz, GHz, THz (*)	This field indicates the start point of the frequency range. Each calibration can correspond only to one frequency range.	1
End Frequency of Measurement Frequency Range	Calibration	positive integer	Hz, kHz, MHz, GHz, THz (*)	This field indicates the end point of the frequency range. Each calibration can correspond only to one frequency range.	1
Validation performed?	Validation Measurement	boolean (*)	-	A validation measurement, or measurements, may be performed after system calibration to enable measurement error or accuracy calculations. Each time validation is performed, a new validation instance is used. Each validation instance includes properties of the type of validation material, the validation material temperature, and the validation time.	1
Validation Identifier	Validation Measurement	string	-	Unique identifier for each validation instance.	m
if(Validation Performed?)=”Yes”, Validation material	Validation Measurement	string (*)	-	If validation was performed, the type of validation material that was used. Each validation instance (i.e., each validation identifier) corresponds to one validation material.	1
if(Validation Performed?)=”Yes”&&”Validation material” = “other	Validation Measurement	string	-	If validation was performed and the validation material was not one of the standard types, enter the type of validation material here.	1
if(Validation Performed?)=”Yes”, Validation material temperature	Validation Measurement	floating point	C, F, K (*)	If validation was performed, the temperature of the validation material.	1
if(Validation Performed?=”Yes”), Validation time	Validation Measurement	floating point	h, min, s, less than (min), less than (h), more than	If validation was performed, the time that the validation measurement was performed at. Note that a single time point, not a range, should be entered.	1

			(min), more than (h) (*)		
if(Validation Performed?="Yes"), literature reference for validation material data or model	Validation Measurement	string	-	In this field, the literature reference(s) for the validation material data or model should be provided in standard IEEE referencing format. Multiple references for the validation material properties may be included.	m
if(Validation Performed?="Yes"), reference to validation data model	Validation Measurement	string/array	unitless, S/m, other	For each validation material, this is the corresponding model validation data. It should be uploaded/stored in array format, or a link to the data location may be provided. Multiple references for the validation material properties may be included.	m
if(Validation Performed?="Yes"), Reference to Validation data	Validation Measurement	string/array	unitless, S/m, other	For each validation instance (i.e., each individual validation measurement), this is the corresponding measured validation data. It should be uploaded/stored in array format, or a link to the data location may be provided.	1
Type of error calculation (between data and model)	Uncertainty Analysis	string (*)	-	After conducting validation measurements, the data is compared to the known model. The resulting error between the measured and known dielectric properties determine the measurement uncertainty. The type of error calculation includes accuracy, repeatability, and total combined error (TCU). Multiple types of error calculations may be performed for each validation measurement.	m
other type of error calculation (between data and model)	Uncertainty Analysis	string	-	List the type of error calculation performed, if not one of listed options. Multiple types of error calculations may be performed for each validation measurement.	m
Error value	Uncertainty Analysis	floating point	unitless, S/m, %, other	The calculated error for the given validation measurement. There may be multiple calculated errors only if multiple types of error calculation methods were used, or if the measured validation data was compared to multiple models.	m
Sample Identifier	Material	string	-	Unique identifier for each sample. An experiment may contain multiple samples.	m
Type of sample	Material	liquid, phantom, biological tissue, other(*)	-	Each sample is of a specific type. The sample type can be liquid (ex: saline, alcohols), phantom (ex: TX151, oil-in-gelatin), or biological tissue (any tissue derived from human or animal sources). If the sample type is not any of these categories the sample type is "other".	1
If (Type of sample in individual measurement) = "Other", other type	Material	string	-	The type of sample, if not liquid, phantom, or biological tissue.	1
If (Type of sample in individual measurement) = "Liquid", liquid type	Material	string	-	The type of liquid sample (ex: saline, alcohol, etc).	1
If (Type of sample in individual measurement) = "Standard Liquid", liquid volume	Material	floating point	uL, mL, cL, dL, L (*)	The volume of the liquid measured.	1
If(Type of sample in individual measurement)= "Phantom", phantom type	Material	string	-	The type of phantom material.	1
If(Type of sample in individual measurement)= "Phantom", phantom composition (recipe)	Material	string	-	If the material is not standard, a list of ingredients or a reference to the material mixture properties may be provided.	1
If(Type of sample in individual measurement) = "Biological Tissue", tissue source species	Material	string (*)	-	The species source of the biological tissue sample. For example, the sample may be human, porcine, etc.	1
If(Type of sample in individual measurement) = "Biological Tissue"&& tissue source species= "other", other tissue source species	Material	string	-	The species source of the biological tissue sample if not one of listed options.	1
If(Type of sample in individual measurement) =	Material	string (*)		The organ or body part of the biological tissue sample.	1

"Biological Tissue", tissue source organ/type					
If(Type of sample in individual measurement) = "Biological Tissue", && tissue source organ/type = "other", tissue source organ type	Material	string	-	The organ or body part of the biological tissue sample, if not one of listed options.	1
If(Type of sample in individual measurement) = "Biological Tissue", tissue diseased or normal	Material	string (*)	-	Indicates whether the sample contains normal, diseased or unknown tissues.	1
If(Type of sample in individual measurement) = "Biological Tissue", tissue source organ/type further information	Material	string	-	This field contains additional information regarding the tissue sample. For example, if the sample is a heterogeneous composition of various tissue types, or if the tissue is diseased what type and grade of disease (if known).	1
If(Type of sample in individual measurement) = "Biological Tissue", animal information	Material	string	-	Miscellaneous information on the animal, for example age, gender, weight, etc.	1
If(Type of sample in individual measurement) = "Biological Tissue", tissue state	Material	string (*)	-	The state of the biological tissue sample being measured. The sample may be excised from the animal/patient (ex-vivo), or the measurement may be conducted in-vivo or in-vitro. Further, the sample may have been excised and then preserved.	1
If(Type of sample in individual measurement) = "Biological Tissue" && tissue state = preserved, preservation process	Material	string	-	If a tissue sample has been preserved prior to measurement, in this property field the preservation process and details should be described, including the type and technique of preservation performed, materials used, the duration of preservation, and any other conditions.	1
If(Type of sample in individual measurement)="Biological Tissue"&&tissue state=ex-vivo, time from excision	Material	floating point	h, min, s, less than (min), less than (h), more than (min), more than (h) (*)	If a biological sample is measured ex-vivo, the time since excision. Note that a single value, not a range, should be entered.	1
If(Type of sample in individual measurement) = "Biological Tissue", tissue sample dimensions	Material	floating point	mm x mm x mm cm x cm x cm (*)	If a biological sample is used, this property details the dimensions of the tissue sample.	1
If(Type of sample in individual measurement) = "Biological Tissue", tissue handling procedure	Material	string	-	If a biological tissue is measured, the sample handling may affect the dielectric properties. In this property, the specific handling procedures should be described, for example, including how the tissue was stored, what type of sample container is used, if the sample is moistened or dried prior to measurement, if the tissue was cut into segments, and so forth. Multiple types of handling procedures may be used with a single sample.	m
Number of samples of same type (if measurements not sample-based or site-based)	MUT Recordings	positive Integer	-	This field is only used if the experiment is looking at measurements/data on a tissue or organ-wide basis, without regard to specific sample or specific measurement site on a sample. In this case, this field indicates the number of samples, of the same type, that measurements are conducted on. All tissue samples may be denoted as a single sample type for metadata collection purposes. No site identifiers are then required, as all sites/samples are analyzed as a whole. Within one tissue sample type, only one value for 'number of samples of same type' may be entered. However, an experiment may contain multiple tissue sample types.	1

Number of measurement averages taken over sample (if measurements are sample-based but not site-based)	MUT Recordings	positive integer	-	Multiple measurements may be taken from a sample and then averaged, resulting in a single data file. This may be done with hardware-based averaging or manually, with measurements occurring at one site or multiple sites. This field applies when site-specific information is not available or not of interest, and therefore the samples are being studied as a whole. Each sample has a fixed number of measurement averages. However, an experiment may contain multiple samples, and each may have a different number of measurement averages.	1
Site identifier (if measurements site-based)	MUT Recordings	string	-	Unique identifier for each measurement site on a sample. An experiment may contain multiple samples, each of which may contain multiple sites.	m
Measurement identifier	MUT Recordings	string	-	Unique identifier for each measurement. Each measurement corresponds to a single dielectric property measurement. If site-based measurements, each site may have multiple measurements conducted on it. If sample-based measurements, each sample may have multiple measurements conducted on it (that are not site-specific).	m
Number of measurement averages taken at individual site (if measurements site-based)	MUT Recordings	positive integer	-	Hardware or manual averaging may be used to reduce measurement noise. This property indicates the number of averages taken to make up one single recorded data measurement at a given measurement site.	1
Measurement Timing	MUT Recordings	floating point	h, min, s, less than (min), less than (h), more than (min), more than (h) (*)	The time of the measurement. Each measurement occurs at a single, fixed time. However, multiple measurements may occur, each with a different time point. Note that a single time point, not a range, should be entered.	1
Location of measurement sites on sample [reference to image file]	MUT Recordings	string / image	-	This property describes the location of the sites on a given sample. The sites may be described in text or through photographic images. Multiple descriptions are possible if there are multiple sites.	m
Reference to measured data [location of data file] or the data itself	MUT Recordings	string or array	unitless, S/m, other (if other, enter the unit)	For each measurement instance (i.e., each individual measurement), this is the corresponding measured data. It should be uploaded/stored in array format.	1
If(Type of sample in individual measurement) = “Biological Tissue”, biological tissue processing information	Sample Analysis	string	-	If a biological tissue sample has been measured, the sample may be subject to sample analysis after the measurement is conducted. This property describes any sample analysis that is conducted post-measurement. For example, this may include marking of the measurement location, tissue preservation, embedding in wax, slicing (slice thickness), staining (stain type), histology (method used), imaging, etc. The parameters and details of each type of sample analysis should be provided. A given sample may be subject to multiple types of processing.	m
If(Type of sample in individual measurement) = “Biological Tissue”, sample histology	Sample Analysis	string / image file	-	The results of the histological analysis should be uploaded / described here. Multiple types of histological analyses and histological images are possible.	m
If(Type of sample in individual measurement) = “Biological Tissue”, sample histology interpretation	Sample Analysis	string	-	The histological interpretation of the site/sample, e.g., “80% healthy gland tissue, 20% malignant”, or “normal tissue”, etc. Multiple types of interpretations are possible for a given sample.	m
Exclusion criteria for measurement data	Dielectric Data Analysis	string	-	In some cases, exclusion criteria to remove data (likely poor data attributed to errors during measurement, but also due to errors in tissue processing post-measurement that affect interpretation of	m

				the data) may be applied. The standard exclusion criteria are based on the Kramers-Kronig relation. The exclusion criteria used to remove recordings should be described here. Multiple exclusion criteria are possible.	
Dielectric model type	Dielectric Data Analysis	string (*)	-	The type of dielectric model used to model the raw data in closed form. Standardly used models are the Cole-Cole and Debye. For each data measurement, multiple models may be applied.	m
if(Dielectric model type=other), other model type	Dielectric Data Analysis	string	-	The dielectric model type, if not one of listed options.	m
Number of poles	Dielectric Data Analysis	positive integer	-	The number of poles used in the dielectric model. Each dielectric model has a fixed number of poles. However, multiple models may be defined each of which has a different number of poles.	1
if(Dielectric model of individual measurement=Debye), parameter list	Dielectric Data Analysis	array in format [pole number, epsilon_inf ,epsilon_static , tau]	[unitless, unitless, unitless, ps]	The parameters used in the Debye model. The parameters are defined as: epsilon_inf = relative permittivity limit as frequency increases epsilon_static = relative permittivity limit as frequency decreases tau = relaxation time constant Each model fit corresponds to a single parameter list. However, multiple models with multiple parameter lists may be defined.	1
if(Dielectric model of individual measurement=Cole-Cole), parameter list	Dielectric Data Analysis	array in format [pole number, epsilon_inf ,epsilon_static , alpha, tau, sigma_static]	can input multiple of: [unitless, unitless unitless,unitless , ps, S/m]	The parameters used in the Cole-Cole model. The parameters are defined as: psilon_inf = relative permittivity limit as frequency increases epsilon_static = relative permittivity limit as frequency decreases tau = relaxation time constant alpha = parameter to broaden dispersion sigma_static = static ionic conductivity Each model fit corresponds to a single parameter list. However, multiple models with multiple parameter lists may be defined.	1
Data to model fit optimization method	Dielectric Data Analysis	string (*)	-	Dielectric data is fitted to dielectric models using fitting algorithms. The fitting technique used is to be noted here. Each data to model fit may involve multiple optimization methods.	m
if(Data to model fit optimisation method=other), other optimisation method	Dielectric Data Analysis	string	-	Dielectric data is fitted to dielectric models using fitting algorithms. If the fitting algorithm is not one of the more commonly used, it should be described here.	m
calculation method for error between data and model	Dielectric Data Analysis	string (*)	-	The method used to calculate the fit error between the data and the model, i.e., how the error or the quality of the fit is determined. For example, average fractional or percent difference over frequency range, chi-squared goodness of fit, etc.	m
Fitting error	Dielectric Data Analysis	floating point	unitless, S/m, %, other	The calculated fitting error between the model and the data. There may be multiple fitting errors for each data set if different error calculation methods were applied.	m