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Evaluating the Dielectric Characteristics of Tissues: A Relationship Between Low Frequency Range and Dryness

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ABSTRACT

The electromagnetic modeling of the human body requires basic parameters, which are characteristics of biological tissues. This review aims at assessing the dielectric characteristics of tissues at varying frequency, temperature and noting the dehydration effect. Using the Patient, Intervention, Comparison, Outcome: PICO as an evidence base practice formula, the review question, "Will exposure to low frequency electromagnetic fields modify the dielectric characteristics of tissues with moisture content much from those that are not exposed?" was broken into key concepts to aid in the search for articles. Findings about the dielectric properties of biological tissues were investigated, taking into account a number of pertinent factors such as the tissues under examination, their temperature, their frequency range, and their level of dryness. Using search engines like Google Scholar, Research Gate, and Science Direct, a preferred reporting item for systematic reviews and meta-analyses (PRISMA) flow chart illustrates how publications within the last two decades plus were found and reviewed. The review's findings highlighted several of the study's weaknesses, including the dehydration effect; scant or not reported and the frequency, where there has been less research conducted at lower frequencies. It was also observed that a low database on dielectric characteristics was typically present in some tissues, regardless of their sensitivity level. Lastly, research that is critical to the development of human body modeling in the future is reviewed.

Keywords:
Dielectric properties,
Biological Tissues,
Low frequency range,
Dehydration of tissues

INTRODUCTION

Numerous types of biomedical applications and various electromagnetic characterization techniques have grown rapidly as a result of the steady growth of the research of dielectric characteristics over time. It has also made enormous contributions to the biophysical and physiological sciences (Fornes-leal et al., 2019).

Three electromagnetic qualities, often known as dielectric properties, permittivity, conductivity, and permeability, are used to describe how electromagnetic waves interact with biological tissue. All cellular, molecular, and ionic organization levels are affected by electromagnetic field interaction with biological tissues, which provides information on potential biological impacts (Gabriel & Peyman, 2018). Various studies have presented measured dielectric data under various circumstances, including temperature, frequency, or time since excision, as well as the kind of technology employed in measuring the dielectric characteristic (Gerazov et al., 2021). When it comes to cancer treatment, such as radiotherapy and hyperthermia, where the temperature and dosage of radiation are adjusted depending on the electrical characteristics of the afflicted tissues, these determined dielectric properties can be utilized to distinguish between cancerous and regular tissues (Silva et al., 2020; Samaddar et al., 2022).

As medical technologies are naturally most interested in data deriving from measurements on human samples, only a small number of research have produced data from these sources yet. The dielectric properties of regular and cancerous tissues have remained of interest in this field of research. A summary of the state-of-the-art and discussion of possible future directions for the dielectric properties of tissues are useful in light of the current status of other investigations. With the development of machine learning methods and big data analysis, the estimation of dielectric characteristics from images has a great deal of potential to advance (Sasaki et al., 2022).

This review's objective is to evaluate how dehydration and low frequency affect the irradiated tissues' dielectric characteristics. Therefore, we have examined the tissues' dielectric data at different degrees of dryness, structural changes of tissues at microscopic view, and correlation between high sensitive and low sensitive tissues, since the development of precise methods of measuring dielectric properties has led to a greater understanding of dielectric phenomena in tissues. For the purpose of consistency throughout this evaluation, the relative permittivity and conductivity are used as the common measurements, unless otherwise specified.

MATERIALS AND METHODS

Dielectric Measurement

Although dielectrics are non-conductive materials, they can conduct when exposed to a strong enough electric field because of a partial ionization that occurs. Thus, we can define dielectric qualities as a material's attributes that characterize its conductivity in an electric field (i.e., its capacity to retain electrical charge). Permittivity, conductivity, resistivity, and loss tangent are a few of them. These characteristics specify how a material reacts to electromagnetic energy that interacts with or travels through it.

Electrical permittivity and magnetic permeability are the two factors that govern electromagnetic field propagation in any given space. The study of a material's dielectric characteristics, particularly permittivity, which is typically described as a function of frequency, is known as dielectric spectroscopy.

Permittivity

A material's permittivity is a property that indicates how much electrical charge it can hold when exposed to an electromagnetic force. The formula for a material's complex permittivity (ε^*) relative to free space is as follows:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \frac{D}{E} \quad (1)$$

In this case, $j = \sqrt{(-1)}$, D is the electric flux density, E is the electric field strength, and ε' and ε" are the dielectric constant and dielectric loss factor, respectively. The permittivity of open space is given by ε_0 (8.854 x 10-12Fm^{-1}), and the relative dielectric constant is given by ε_r' such that;

$$\varepsilon_0 = \frac{\varepsilon'}{\varepsilon_r'} \quad (2)$$

The real component of the dielectric constant is denoted by ε' and it is the material's stored energy in the presence of an electromagnetic force. The factor ε" for dielectric loss is as well-known as the imaginary component, which affects attenuation and energy absorption. The impacts of conductivity and dielectric loss are also included in the loss factor ε". The loss tangent (tanδ) is another important dielectric parameter, and it describes the energy lost by the material as electrical signals pass through it.

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{2\pi f\varepsilon} \quad (3)$$

Where σ is the conductivity of the material, ε is the permittivity (8.854x10^{-12} Fm^{-1}), and f is the frequency respectively.

Search Strategy

In this review, the PRISMA flow diagram technique was taken into consideration when retrieving papers. The databases Science Direct, Google Scholar, and Research Gate were searched for articles published during the last twenty years that dealt with the assessment of biological tissues' dielectric characteristics. With the use of PICO, Keywords such as; Dielectric Properties, Tissue dehydration, Tissue permittivity, Conductivity, High Sensitivity tissues, Low Sensitivity tissues, Temperature dependence, biological system modeling were used to search for articles. Additional articles were gotten from reference list of publications.

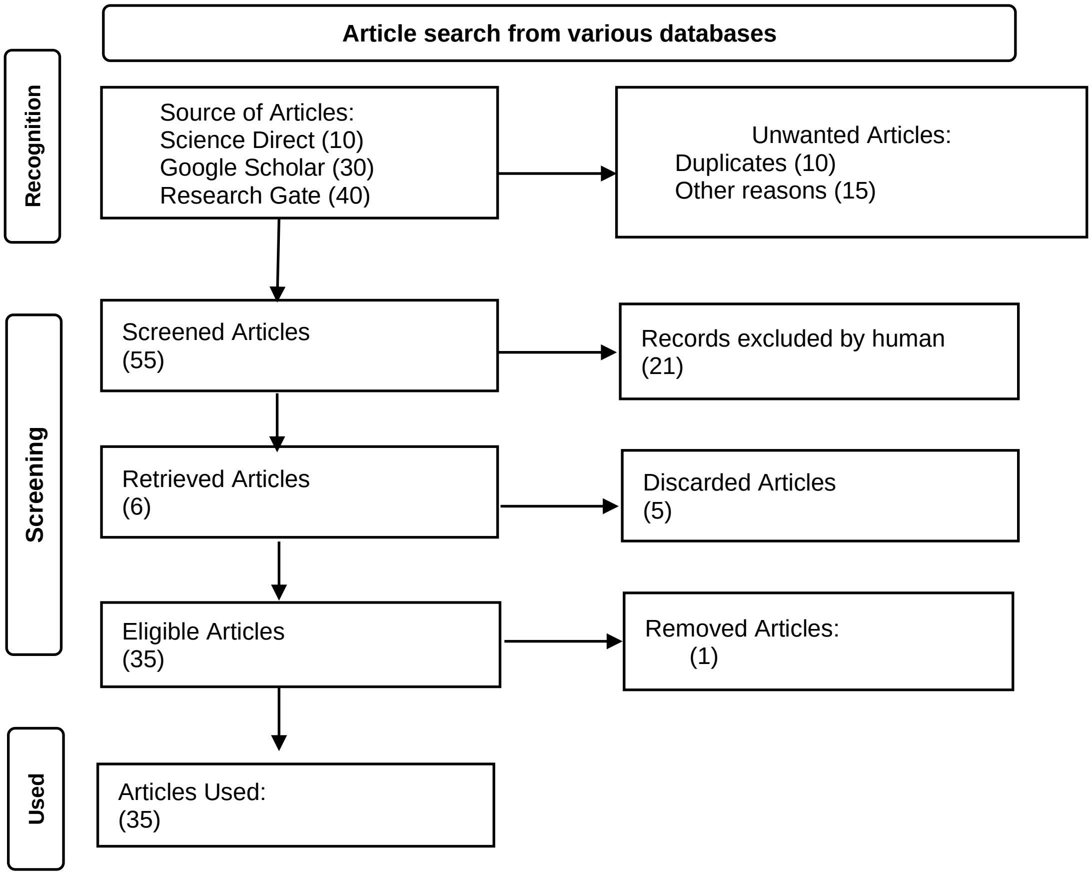

Figure 1: PRISMA Flow Chart

Selection Criteria

Books, and chapters were excluded. Our selection criteria were based on previous similar works with full access to English language text, reporting about the effects of dehydration on dielectric properties, dielectric properties of high sensitive and low sensitive tissues, and microscopic view of structural changes to tissues.

Table 1: Results of Synthesized Reviews on the Dielectric Properties of Different Tissues

Investigators	Frequency range	Tissue type	Source	State	Tissue Temperature	Effect of Dehydration
Peyman et al., 2009	50 MHz – 20 GHz	Brain, Bone marrow, skull	Porcine	In vitro	37^0C	Alteration in the dielectric characteristics when an animal aged because of a decrease in water content.
El Khatib et al 2010	100 Hz to 5 MHz	Liver, Kidney, Muscle	Rat	In Vitro	Not Specified	Not Reported.
Wolf et al., 2011	1 Hz – 40 GHz	Blood	Human	In Vitro	Not stated	Not reported.
Karacolat et al., 2012	300 MHz – 3 GHz	Skin	Pig	Ex Vivo	38^0C-39^0C	Not reported.

Shahzad et al., 2017	500 MHz to 20 GHz	Liver	Nude Mice	Ex Vivo	22 ± 0.8^{0}C	The effects of dehydration are expressed as a time function.
Bonello et al., 2018	0.5 GHz to 8 GHz	Lung	Ovine	Ex Vivo	25 - 91^{0}C	Not Reported.
Elwan et al., 2018	10^6 Hz – 3x10^9 Hz	Liver, Bone marrow	Rat	In Vitro	Not Stated	Not reported.
Sombo et al., 2018	0 to 100 KHz	Blood, Liver, Kidney	Bovine	Ex Vivo	37.0 ± 0.5^{0}C	Significant effect of water content.
Fornes-Leal et al., 2019	0.5 – 26.5 GHz	Abdominal, Thoracic	Porcine	In Vivo	21^{0}C	Not Reported.
Maenhout et al., 2020	500 MHz to 20 GHz	Liver	Porcine	Ex Vivo	22.6–37.7^{0}C	There was significant effect with respect to time.
Silva et al., 2020	Not Reported	Liver	Ovine	Ex Vivo	25-97^{0}C	The excision-related dehydration might not have a big effect on the property values.
Tyovenda et al., 2020	0.0001-0.5GHz	Liver	Rat	Ex Vivo	Not specified	Not reported.
Gerazov et al., 2021	500 MHz to 50 GHz	Muscle	Rat	Ex vivo	25^{0}C	10% - 70% dehydration achieved.
Istuk et al., 2021	500 MHz to 20 GHz	Heart	Sheep	Ex Vivo	23.5±0.9^{0}C	No significant effect.
Aydinalp et al., 2022	0.5 to 20 GHz	Skin	Mimicking Phantom		24±2^{0}C	Not Reported.
Kirubakaran et al., 2023	Not Specified	Hand, stomach, thumb, finger, pancreas	Human	Ex Vivo	Not stated.	Not reported.
Buisson et al., 2023	100 MHz to 2 GHz	Liver	Mouse	Ex Vivo	Not Specified	Not Reported.

RESULTS AND DISCUSSION

The α-, β-, and γ-dispersions occur at very low frequencies and reach several hundred GHz, and they govern the dielectric characteristics of tissues. At frequencies lower than 10 kHz, the mobility of cell ions inside the tissue is thought to be associated with α-dispersion. Water molecules' dipole moment rotation and interfacial polarisation at the tissue's cell membrane interface are the causes of β-dispersion in the MHz band and γ-dispersion in the GHz band, respectively.

Since most tissues are composed primarily of water, the electrical properties of the water content influence the dielectric properties of tissues to some extent. Within the γ-dispersion frequency band, the dielectric properties of water are temperature dependent: at temperatures between 20 and 40 ^{0}C, pure water's relaxation frequency falls between 16 and 27 GHz (Ellison, 2007). This finding implies that there is a significant temperature dependence on the dielectric characteristics of water in tissues in the γ-dispersion frequency range, or roughly between 10 and 100 GHz.

Furthermore, the dielectric properties of tissues can be influenced not only by the γ-dispersion but also by other water scattering characteristics. For pure water, an empirical formula integrating the Lorentz and multi-pole Debye models has been applied for frequencies up to about 30 THz (Ellison, 2007; Liebe et al., 1991).

Dielectric Measurement Method

The most popular method for measuring dielectric characteristics lately is the coaxial probe method since it is simple, non-damaging, and straight forward (Gerazov et al., 2021; Samaddar et al., 2022). According to research, while evaluating the dielectric characteristics of tissues, probes with smaller aperture diameters and lower sensing depths should be utilized to improve measurement accuracy (Aydinalp et al., 2022).

The dielectric measurement of tissues procedure has been reviewed, and recommendations for the measurement process have been provided (Gioia et al., 2018). Another way for determining the dielectric properties is the use of an impedance meter in conjunction with signal generators to determine the samples' capacitance and dissipation factor (Sombo et al., 2018).

Dielectric Characterization of Biological Tissues

Wolf et al. (2011) ascertained the complex permittivity and conductivity across a wide frequency range (1 Hz to 40 GHz), various dielectric testing techniques were integrated. From the use of a Novo Control Alpha-A Analyzer, to the use of a coaxial reflection method using an impedance analyzer E4991A with the Agilent 4294A auto-balance bridge was also used. Likewise, dielectric probe kit 85070E with an E8363B PNA series network analyzer was used to cover a wide frequency range. Blood did not exhibit any α-relaxation, as noted by the writers. Furthermore, the β-relaxation analysis using typical cell models produced somewhat illogical results for the inherent dielectric characteristics. Moreover, a distinct dispersion effect was noted in the vicinity of the β- and γ-relaxations, which is commonly associated with the δ-relaxation.

Peyman et al. (2009) measured the relative permittivity and conductivity of porcine tissues using the open ended coaxial probe and a computer controlled network analyzer (Agilent 8720D) at a frequency range of 50 MHz – 20 GHz. The internal diameters of the probes used were 1.67mm and 2.98mm. For the majority of the studied tissues, the authors found a systematic variation in the dielectric characteristics with age which are mostly caused by the tissues' decreased water content.

A gamma irradiator was applied to the investigation of its effect on the radiofrequency dielectric properties of bovine kidneys. Calculations were conducted to establish mathematical models for the dielectric structural parameter, dielectric spread parameter, dielectric decrement, and dielectric relaxation time. The polynomial functions of degrees 4, 4, and 5 that make up these mathematical models have coefficients of fit for dielectric decrement, relaxation time, and spread parameter of 98.2, 83.9, and 99.5, in that order. It demonstrated how the models might be used to produce dielectric data that would help forecast the degree of kidney tissue damage in the gamma irradiation dose range (Agba et al., 2014).

In order to assess the sensitivity level of typical parameters, such as liver enzymes and tissue histopathology, in order to distinguish between the effects of two dose rates, Elwan et al. (2018) conducted a study in the frequency range of 10^6 Hz – 3 x 10^9 Hz using an impedance analyzer (E4991B) from Keysight Co., USA. Liver samples and bone marrow samples were extracted following the dissection of rats under anaesthesia. They were previously exposed to irradiation from a ^{60}Co gamma radiation source at 20^0C under air atmosphere. The dose rates, which were determined using a secondary standard dosemeter system consisting of a 0.6cc ionisation chamber combined with a calibrated electrometer, were 533.35mGy/min and 325.89mGy/min. After that, the samples were processed and alcohol was used to dehydrate them. Sections 5µm thick were stained for histopathological analysis using a CX41 Binocular microscope equipped with a SC100, 10.5MP digital camera and image capture software from Olympus Co. The sensitivity of the classical parameters varied, according to the results. On the other hand, the bone marrow's dielectric characteristics demonstrated a strong sensitivity to the impact of both high and low dose rates.

Sombo et al. (2015) developed mathematical models of the dielectric dispersion properties of bovine liver at low radiofrequency by using a gamma irradiator. They discovered that the dielectric spread parameter, dielectric decrement, and dielectric relaxation time had coefficients of fit of 94.0%, 74.6%, and 96.0% at low frequencies and 97.8%, 99.8%, and 98.2% at radiofrequency in relation to the irradiation dosage. This proved that there is a dose-associated alteration in the irradiated cow liver tissue.

Shahzad et al. (2017) noted the effects of tissue drying on the excised tissues' dielectric characteristics. Using a slim form dielectric probe Keysight 85070E with a Vector Network Analyzer (VNA) keysight E8362B, they measured the electrical properties within the frequency range of 500 MHz – 20 GHz. The technique used is known as coaxial probe method and measurements were done within 3.5hrs after excision at intervals of 30 minutes each. As a function of time following excision, they noticed a notable alteration in the tissue's conductivity and dielectric constant. Same temperature was maintained all through the experiment.

Sombo et al. (2018) used an improvised parallel plate dielectric cell with an impedance meter working with a signal generator in order to determine the dielectric spread parameter of gamma radiation within the dose range of 1.0–85.0 Gy for tissues such as blood, liver, and kidneys. Findings from this research showed that at 0-50 MHz, the kidney tissue under test displayed higher sensitivity, followed by liver tissues and lasted the bovine blood between 0-60 Gy, but the reverse was the case for blood and liver at 85 Gy. The kidney has the highest sensitivity to radiation, followed by blood and liver tissues at roughly 43–85 Gy. Liver tissue is generally more susceptible to radiation effects between the gamma irradiation dose range of 0–20 Gy and frequency range of 0–100 kHz. Based on this research, liver tissue is less prone to radiofrequency radiation damage. The linear model was shown to be the most appropriate in explaining how gamma radiation affects the dielectric dispersion characteristics of bovine tissues at both low and high radiofrequencies when compared to the exponential and polynomial models. Consequently, a linear relationship exists between the gamma irradiation dose and the response of the studied tissues.

Tyovenda et al. (2020) analysed the impact of X-rays on the dielectric characteristics of tropical and albino rats' livers. New data on the livers of albino and tropical rats in the frequency range of 0.0001 to 0.5 GHz and peak voltages of 50 kV–70 kV were obtained through the application of measurement and analytical procedures. For both irradiated and non-irradiated liver tissues of albino and tropical rats, conductivity, dielectric permittivity, and dielectric loss factor were measured. The findings demonstrated that variations in x-ray and frequency dosages had a significant impact on the dielectric characteristics of mammalian tissues. When comparing the RF dielectric characteristics of comparable tissues to the cited studies, their detection method and analytical process were determined to be in good agreement.

Salahudin et al. (2018) proposed that the heart is a heterogeneous organ and not homogeneous, as suggested by previous literature. It's possible that assuming the heart to be a homogeneous organ will lead to an inaccurate dielectric representation of the entire structure. Therefore, Istuk et al. (2021) considering the heart as a heterogeneous organ, they determined the heart's and its major vessels' respective dielectric characteristics. The results showed that the distinct parts of the heart had varying dielectric properties. They demonstrated how results from dielectric property measurements might be affected by heterogeneity and tissue dryness. They went ahead to measure the dielectric properties of the heart using the coaxial probe method at various points inside and outside of the heart over the 500 MHz to 20 GHz frequency range. At a single frequency (2.4GHz), every component of the heart's dielectric characteristics was evaluated. by the authors. They also discovered variations in the dielectric characteristics of certain cardiac regions, which supported the heterogeneity of the heart.

In 51 cases of oesophageal cancer, the dielectric measurement of normal and tumour tissues was performed immediately after resection using an open-end coaxial probe operating in the frequency range of 50 MHz to 4 GHz. In addition to statistically analysing the measurement results at different frequencies, the tissue's differences in dielectric properties were examined. Additionally, they employed the Cole–Cole model to fit data across the whole frequency range, and the observed data suited the model well. Furthermore, they observed notable variations in the dielectric characteristics of the tumour and normal oesophageal tissues, which offer a theoretical foundation for prompt detection of oesophageal cancer after surgery (Qiang et al., 2021).

High accuracy in the measurement of dielectric characteristics using the open-ended coaxial approach depends on the sample's dimension and the probe's placement. Nonetheless, the experimental condition determines both. Cavagnaro & Ruvio, 2020 demonstrated how a numerical analysis may be used to determine the inaccuracy resulting from the reconstruction process under the particular setup circumstances. For this experiment, a Vector Network Analyzer and Keysight Slime Form Probe were utilised. The investigators pointed out that the most important factor affecting the accuracy of the reconstruction for tissues with high water content is the depth at which the probe is inserted into the sample. In contrast, the probe could be only brought into touch with the sample surface when the water content is low; nevertheless, a deeper and wider sample is needed to reduce biasing effects from the background environment.

An effective way to control the error associated with the open-ended coaxial probe (OECP) approach is to choose a probe with a good sensing depth (SD). In order to achieve this, Aydinalp et al., 2022 examined the standard deviations of probes using three distinct aperture sizes: 0.5, 0.9, and 2.2 mm. The SDs of the probe was examined using simulations with a double-layered sample setup and a commercial OECP with a 2.2 mm aperture diameter. The scientists discovered that when evaluating the dielectric characteristics of tissues, probes with smaller aperture sizes (in this case, 0.5mm) and smaller SD should be employed to improve measurement accuracy.

Measurements of dielectric permittivity in the microwave range were evaluated in fatty and healthy liver tissue. Buisson et al., 2023 showed the alteration in triglyceride and glucose concentrations in the hepatic tissue of HFS diet mice using a mouse model that was fed both normal and high sugar/glucose (HFS) diets. Between 100 MHz and 2 GHz, they noticed variations in the dielectric permittivity of fatty and healthy livers. At 1 GHz, the dielectric permittivity was measured in the healthy and fatty liver tissues, and it was found to be 42 in the former and 31 in the latter. This indicated that dielectric permittivity can be a sensitive method for differentiating between the two types of hepatic tissue.

Between 500 MHz and 20 GHz, Maenhout et al., 2020 observed the impact of various probe-to-tissue measurement contact pressures. on exerting consistent pressure on the sample while taking measurements, they built a lifting platform with a built-in pressure sensor. A combination of a Pressure Network Analyzer E8361 keysight USA and a N1501A keysight slim form probe were used to test the dielectric property and relative humidity, respectively, using the HDC108DEVM instrument. In the pressure range of 7.74kPa to 77.4kPa, they also found a linear connection for the relative real and imaginary complex permittivity of -0.31 ± 0.09% and -0.32 ± 0.14% per kPa. Moving towards a standardised probe-to-tissue contact pressure is advised since research has demonstrated that repeating the procedure at the same pressure can yield repeatable results with a 1% uncertainty interval.

Zhekov et al. (2019) reported on the dielectric characteristics of human hands measured in vivo with a coaxial probe between 5 and 67 GHz. Thumbs and palms of twenty-two volunteers were measured in both wet and dry conditions. Additionally, parametric models were created for each component and circumstance using a single-pole Cole-Cole model. The permittivity of the dry thumbs and palm differed by only 10%. For conductivity, similar fluctuations of up to roughly 10% were seen in the frequency range up to around 20 GHz; at higher frequencies, the difference increased to up to 27%. These observations, according to the authors, are caused by the structure of the skin. Additionally, the authors report that there were notable differences in the test subjects' dielectric properties.

Karacolak et al. (2013) obtained skin samples from 20 – 30 month old female pigs and preserved at pig body temperature by being covered in aluminium foil and kept in a water bath. In order to reduce fluid loss and temperature fluctuations, the experiment was carried out within two hours of excision. For the measurement, an Agilent 85070E dielectric probe kit and an E8362B PNA network analyzer were utilised. The sensing depth probe employed was 3.5mm. The authors then fitted the dielectric characteristics as a function of frequency to a three-pole Cole-Cole model. The information gathered suggests that measurements of medical applications meant for human tissues may be made using swine tissue both in vitro and in vivo.

In order to apply microwave diagnostics, Sugitani et al., 2015 measured the dielectric properties of human breast tissues (cancer, stroma, and adipose tissues) in vitro between 0.5 and 20 GHz using a coaxial probe. 35 patients, ranging in age from 33 to 88, who underwent cancer operations provided the tissue samples. The dielectric measurements were conducted between 18 °C and 24.1 °C. Furthermore, reports of two-pole Cole-Cole parametric models were made.

Sasaki et al. (2015) examined in vitro at 35 °C between 0.5 and 110 GHz the dielectric properties of the cornea, aqueous fluid, vitreous humour, sclera, and iris using a coaxial probe. Except for the porcine aqueous humour, all ocular tissues were obtained from rabbits. They found that the aqueous humor's dielectric properties were almost exactly the same as those of pure water at frequencies higher than 13 GHz.

Using a coaxial sensor, Mizuno et al., 2021 investigated the dielectric characteristics of cornea in vitro at about 35 °C. Cornea from rabbits and pigs were evaluated for similar characteristics. They observed that the primary reason of the variations in dielectric properties was variations in water content, which is the primary component producing individual aberrations.

Numerical simulations were employed by Farshkaran & Porter, 2022 to examine the sensing volume of the Keysight slim-form open-ended coaxial probe. Calculated sensing depth and radius were used to define a hemi ellipsoidal sensing volume for the probe, and its accuracy was examined. The sensing volume is more accurately represented as a hemi ellipsoid than as a cylinder, according to the results. Additionally, the electric field distribution near the probe provides additional evidence for the suggested sensing volume's accuracy.

Putzeys et al. (2021) used a two-electrode technique to study the human perilymph's dielectric properties in vitro at 37 °C between 0.1 Hz and 10 MHz. At a controlled temperature, It was noted how the dielectric properties changed over the course of 48 hours after excision; up to 11 hours following excision, no discernible change was seen. They found a distinct difference between data from recently taken samples and ones that had been frozen in the past.

Huang et al. (2021) reported that the dielectric characteristics of normal and cancerous thyroid nodules as well as in vitro normal thyroid tissue were different. Tissue samples from 155 patients were taken, and the dielectric characteristics were evaluated from 1 to 4000 MHz using a coaxial probe. Based on measured data, the degree of malignancy can be connected with dielectric characteristics, the 20–70 MHz frequency range showing the largest statistically significant variation across the various tissue types. Additionally, a two-pole Cole–Cole model was fitted to the collected data.

It is well known that even in cases where a material being tested is unable to meet the minimal sample geometry requirements, direct spectroscopic measurements utilising a commercial open-ended probe can still be conducted. Therefore, from 0.5 to 8 GHz, measurements of biological tissues with low mechanical strength are dependable, and little differences were seen when the probe location was changed in the material being tested (Samaddar et al., 2022).

Tissue dielectric property variability brought on by measurement-specific conditions

The dielectric characteristics of tissues were measured using an invasive technique, as the previous reviews have shown. To be more precise, the dielectric characteristics were usually measured from electromagnetic reactions that happened when a probe or electrode terminal made contact with the tissues. The dielectric properties of living tissues are the main subject of electromagnetic modeling of the human body. However, only a limited number of conditions allow for the performance of the measurement in the necessary state. As a result, different tactics—like employing animal subjects or conducting studies at room temperature—have been applied in carefully controlled settings.

Furthermore, because regulating the tissue conditions can be challenging, dielectric measurements may not always be repeatable, even when carried out in the intended state. Thus, research reporting differences in tissue dielectric characteristics as a result of measurement-specific factors have been summarized.

Discussion

Several studies have gathered data regarding the dielectric properties of different biological tissues, with particular attention to the temperature and frequency range of the tissues under investigation. When one takes into account the biological diversity of tissues and the different measuring methods employed in different experiments, the results are rather consistent. Nevertheless, conductivity and permittivity data are scarce and very variable at frequencies lower than 500 MHz. This is most likely the result of measuring technique uncertainties (e.g., electrode polarization). However, in both medical applications and exposure assessments for humans, the dielectric characteristics of tissues at lower frequencies are crucial. Thus, precise assessment of the dielectric characteristics of such tissues at frequencies lower than 10 kHz, is considered a critical area of study needed.

There was a substantial variation seen in the literature data for adipose tissues depending on the water or adipose content. Table 1 summarises the impact of water content on the dielectric characteristics of tissues and shows that dehydration significantly affects dielectric properties over time (Maenhout et al., 2020). Furthermore, there may be little to no effect on the property values from the dehydration associated with the excision (Silva et al., 2020). Further developments in the electromagnetic modeling of the human body can be anticipated if the relationship between the dielectric characteristics and the distribution of the water/fat content in adipose tissue can be elucidated. The dielectric characteristics of biological tissues can be greatly impacted by dryness. Tissue becomes more electrically conductive as a result of an increase in the tissue's dielectric constant and loss factor. Therefore, greater investigation is needed into how it affects the dielectric characteristics of different tissues.

The range of error remains high and the quality of dielectric property estimation is still not precise enough. Validating various approaches' correctness in a transparent and effective manner remains a tough task. Due to its capacity to learn from comparatively big datasets, deep learning techniques are becoming the preferred approach.

Taking into cognizance of the temperature, frequency, time, and dehydration level, research at low frequency with respect to high and low temperature correlation is not properly covered. Also, looking at the time from excision for dielectric measurement as a result of dehydration of such tissues in question need to be further stated.

There seems not to be much data on the vulnerability of these tissues at various dose range based on their sensitivity as well as the structural damage to tissues due to radiation under a microscope.

Furthermore, with multiple dielectric measurements over time, there is no much data on the dielectric properties and prediction using the Debye and Cole-Cole models of freshly excised tissues samples subjected to same physical principle of dehydration.

CONCLUSION

Based on this search approach, this research reviewed the dielectric characteristics of biological tissues. This review took into consideration current developments in the electromagnetic modeling of the human body and concentrated on frequency changes, dehydration levels, and general tissues. A variety of frequencies and tissue types were covered in the discussion of the factors influencing the dielectric characteristics of tissues. The review discusses the detailed additional research that is needed in each of the topics in order to make future advancements in the electric modeling of the human body, which is critical for the study of areas of human protection from non-ionizing radiation and biomedical applications.

Although the dielectric characteristics of biological tissues are addressed, the bulk of the research has been conducted in narrowly defined areas. Few studies have addressed important factors like the tissues under investigation, the frequency range employed, the temperature of the tissues, or the hydration effect (moisture content) of sampled tissues during measurements, despite the large amount of research on the dielectric characterisation of tissues that has been done thus far. These qualities are important, but there is no accepted method for measuring them. Additionally, because dielectric data is reported differently in the literature for some tissues (such as the pancreas, small intestine, testis, thyroid gland, and bone marrow), it is challenging to compile and analyse dielectric data from various research.

There are numerous methods for measuring dielectric properties, including waveguide, scalar and vector network analyzers, coaxial probes, resonance structures, impedance analyzers, and parallel capacitors. The parallel capacitor method is appropriate for these kinds of measurements since it is straightforward, dependable, and accurate. Due to its resistance to oxidation and corrosion, platinum is utilised in the construction of the parallel capacitor. The review offered, serves as inspiration for the creation of precise dielectric measurement procedures and the inclusion of all relevant factors to close any gaps in the dielectric data is already accessible.

The following recommendations are noted; that extensive research should be done on each of the biological tissues such as; bone marrow, small intestine, testis/ovary, pancreas, thyroid gland, and stomach wall. Their dielectric properties measured after irradiation, at low frequency and high frequency range and their correlation. Also, dielectric characterization of these tissues covering parameters of interest such as hydration effect (moisture content) and post-mortem effect should be extensively done. Furthermore, correlation of the dielectric characterization of high radiosensitive tissues to those of low sensitivity should be looked into and recovery time of tissues should be examined and monitored after irradiation.

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