ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

CHARACTERIZATION OF TEMPERATURE DEPENDENT DIELECTRIC PROPERTIES OF BIOLOGICAL TISSUE PHANTOMS USING AN OPEN-ENDED COAXIAL PROBE

M.Sc. THESIS

Tuğçe TUTUK

Department of Electronics and Communication Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

VÜCUT DOKULARINI TAKLİT EDEN FANTOMLARIN ISIYA BAĞIMLI DİELEKTRİK ÖZELLİKLERİNİN AUKP YARDIMIYLA ÖLÇÜLMESİ

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HAZİRAN 2024

Tuğçe TUTUK, a M.Sc. student of ITU Graduate School student ID 504211415 successfully defended the thesis entitled "CHARACTERIZATION OF TEMPERATURE DEPENDENT DIELECTRIC PROPERTIES OF BIOLOGICAL TISSUE PHANTOMS USING AN OPEN-ENDED COAXIAL PROBE", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : **22 May 2024**
Date of Defense : **11 June 2024**

To my family,

FOREWORD

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TABLE OF CONTENTS

Page

ABBREVIATIONS

VNA	**:**	Vector network analyzer
OECP	**:**	Open ended coaxial probe
MHz	**:**	Megahertz
GHz	**:**	Gigahertz
PNA-L	**:**	Purpose network analyzers
DAK	**:**	Dielectric assessment kit
PVCP	**:**	Polyvinyl chloride plastisol phantoms
OSL	**:**	Open short load

SYMBOLS

ε	:	Epsilon
ω	:	Omega
ϑ	:	Thita
ε'	:	Epsilon prime
ε''	:	Epsilon double prime
τ	:	Tau
mS	:	Metre per second
ps	:	Petasecond
ns	:	Newton-second
fs	:	Static frictional force
muS	:	Epsilon
gr	:	Grade
MW	:	Microwave

LIST OF TABLES

Page

LIST OF FIGURES

CHARACTERIZATION OF TEMPERATURE DEPENDENT DIELECTRIC PROPERTIES OF BIOLOGICAL TISSUE PHANTOMS USING AN OPEN-ENDED COAXIAL PROBE

SUMMARY

The dielectric characteristics of biological tissues, particularly at microwave frequencies, are essential for various medical applications, including imaging, therapy, and cancer treatment. This research focuses on understanding how electromagnetic waves interact with tissues and the temperature-dependent changes in tissue dielectric properties. Because these treatment procedures occur at temperatures beyond room temperature, the resulting change in tissue dielectric properties must be considered.

Electrical tissue qualities have an immediate effect on the absorption of electromagnetic energy, which results in a heating generation; these features are thus critical to early-stage and clinical uses utilizing electromagnetic waves for heating, as well as thermal treatments in total because dielectric characteristic changes following heating will influence tissue distribution of temperatures and the ensuing thermal harm. For this reason, there is a need for biological phantoms that mimic the dielectric properties of tissues at these high frequencies and different heat rates.

Tissue-mimicking phantoms, such as gelatin-based phantoms, play a crucial role in simulating tissue properties for research and clinical purposes. Many different forms of phantom materials can be used to mimic different tissues. One of the most preferred ones is phantoms produced using gelatin because they are affordable, easy to produce, made from easily available materials and stable. Dielectric properties are not directly measurable characteristics.

Therefore, the data collected from measurement devices are converted into dielectric properties. Although there are multiple methods in the literature for this, the open-ended coaxial probe technique was preferred to measure the dielectric properties of these prepared oil-in-gelatin phantoms and to measure temperature-dependent changes. It is a widely used measurement technique that provides wide frequency range measurements for both in vivo and ex vivo environments.

The mathematical method used to interpret measurement results and compare them with real tissues is Cole-Cole equation. All prepared tissue phantoms were measured first at room temperature and then at all temperatures from body temperature to 55 degrees using an open-ended coaxial probe. The obtained dielectric properties were compared with previous studies and the dielectric properties of real tissues available on the IFAC website and focused on the analysis of the change of dielectric properties with temperature.

The findings obtained as a result of the experiments showed that oil in gelatin phantoms are successful material for tissue mimicking. As a result of the comparisons, it was proven that the dielectric properties of the phantoms were compatible with real tissues

and that they still showed tissue dielectric properties as a result of heating and cooling processes.

VÜCUT DOKULARINI TAKLİT EDEN FANTOMLARIN ISIYA BAĞIMLI DİELEKTRİK ÖZELLİKLERİNİN AUKP YARDIMIYLA ÖLÇÜLMESİ

ÖZET

Mikrodalga frekanslarında enerji yayan cihazların, görüntüleme, terapi ve kanser tedavisinde kullanılmaya başlanmasıyla, dokular ile elektromanyetik dalgalar arasındaki etkileşimleri incelemeye yönelik araştırmalar artmıştır.

Bu çalışmalarda, elektromanyetik dalgaların dokularla nasıl etkileşime girdiğini, dokuların dielektrik özelliklerinde meydana gelen elektriksel farklılıklara odaklanılmışdır. Bir diğer araştırma konusu da teşhis ve tedavi için kullanılan mikrodalga enerjisinin dokuda meydana getirdiği ısı artışının sonuçlarıdır çünkü dielektirik özellikler elektromanyetik enerjinin emilimi üzerinde anında etkiye sahiptir ve bu doku da ısınma oluşumuna neden olur.

Dokulardaki bu ısı artışının sonrasında dielektrik özelliklerde meydana gelen değişiklikleri bilmek, sıcaklıkların dokuda nasıl bir dağılım gösterdiğini ve bunun sonucunda ortaya çıkabilecek zararı da ön görmemizi sağlayacaktır.

Elektromanyetik dalgaların kullanıldığı erken aşama teşhis yöntemleri ve klinik kullanımların yanı sıra ablasyon gibi termal tedaviler içinde ısı sonrası meydana gelen değişimleri anlamak kritik öneme sahiptir. Ancak her vücut dokusu için bu değişimleri laboratuvar ortamında in-vivio ya da ex-vivo deneylerini yapmak mümkün olamayacağı için vücut özelliklerini taklit etmemize yarayan malzemeler olan ihtiyaç doğmuştur.

Literatürde farklı malzemelerden elde edilmiş birçok fantom türü vardır. Fantomlar yapılırken çok farklı ana malzemeler kullanılabilir. Örneğin hidrojel, polivinil alkol, jelatin, agar, plastik gibi malzemelerden fantomlar üretilmiştir. Hem ucuzluğu hem üretim kolaylığı hem de stabil formları nedeniyle bu çalışmada jelatin fantomlar tercih edilmiştir.

Laboratuvar ortamında fantom üretmek içinde farklı metotlar kullanılabilir. Jelatin fantomlarının bir diğer avantajı da kolay bulunabilen malzemeler kullanılarak üretilebilmeleridir.

Deneyde kullandığımız fantomlar da jelatin, distile su, ay çiçek yağ, bulaşık deterjanı ve formaldehit kullanılmıştır. Her malzemenin bir kullanım amacı vardır. Jelatin, yoğunluğu ve optik özellikleri insan dokusuyla benzerlik gösterdiği için kullanışlı bir ana malzemedir ayrıca ucuz ve kolay bulunabilir. Distile su, vücut dokularında yüksek oranda su içermesi nedeniyle üretilen fantomun içerdiği su miktarıda dokuya benzerlik için önemlidir. Ayrıca distile su, jelatinin yoğunluğunu ayarlamak içinde gereklidir. Ayçiçek yağı, dokulardaki yağ oranını simüle etmek için gereklidir. Vücuttaki her dokunun farklı bir yağ yüzdesi olduğu için görüntülemede de yağ oranı dokuları

ayırt etmede büyük öneme sahiptir. Bulaşık deterjanı, fantom içindeki malzemelerin homojen bir şekilde karışmasını sağlayabilir ve jelatinin sıvı içerisinde homojen bir şekilde dağılmasına yardımcı olur. Ayrıca fantomun yüzey gerilimini azaltarak kabarcık oluşumunu engeller. Son kullandığımız malzeme olan formaldehit jelatinin sertleşmesini sağlayan bir çapraz bağlayıcıdır. Bu, jelatinin istenilen şekli almasını ve fantomun dayanıklı bir yapıya sahip olmasını sağlar. Bu beş ana malzemeyi kullanarak referans aldığımız makaledeki oranlara göre farklı yağ yüzdelerine sahip birçok fantom hazırlanarak çeşitli dokulara benzer özellikler elde edilmeye çalışılmıştır. Bu aşama için on üç adet fantom hazırlanmıştır. Bu fantomların yağ yüzdesi %0 yağ dan %55 yağ oranına kadardır. İlk yapılan fantom hiç yağ kullanılmadan hazırlanmış daha sonraki her fantom da yağ % 5 oranında arttırılarak üretilmiştir. Böylelikle yağ oranının fantomlarda ki elektriksel özelliklerde ki etkisini daha iyi anlamamızı sağlamıştır.

Üretilen tüm fantomların üretim gününden yaklaşık dört gün sonra açık uçlu koaksiyel prob yardımıyla ölçülmüştür. Dört gün sonra ölçüm nedeni ise fantom hazırlanırken kullanılan formaldehitin yağ moleküllerine bağlanarak fantomun istenilen katılıkta oluşması için gereken minimum süre olmasıdır. Ancak dielektrik özellikler doğrudan ölçülebilen özellikler değildir. Bu nedenle ölçüm cihazlarından toplanan veriler dielektrik özelliklere dönüştürülür. Bunun için birden fazla yöntem bulunmasına rağmen hazırlanan bu jelatin içinde yağ fantomlarının dielektrik özelliklerini ölçmek için açık uçlu koaksiyel prob tekniği tercih edilmiştir.

Açık uçlu koaksiyel prob hem in vivo hem de ex vivo ortamlar için geniş frekans aralığı ölçümleri sağlayan, yaygın olarak kullanılan bir ölçüm tekniğidir. Bu yöntemde, dielektrik malzeme ile birlikte bir koaksiyel kablo kullanılır. Koaksiyel kablo, içte iletken bir tel, etrafında dielektrik bir malzeme ve en dışta iletken bir kalkan bulunur. Deney esnasında kullanılan Dak prob sayesinde, prob fantoma direk temas ederek ölçümler alınmıştır. Prob ölçülen malzemenin dielektrik sabitini ve kayıp faktörünü ölçerek malzemlerin dielektrik özellikleri hakkında bilgi edinmemizi sağlar.

Prob ağ analizörüne bağlandıktan sonra proba mikrodalga sinyaller gönderilmeye başlanır. Bu sinyal, dielektrik malzeme içinden geçerken etkileşime girer. Probun ucu ölçüm yapılacak malzeme olan fantoma yerleştiririlirildiği için malzemeden geçen sinyal dielektrik sabiti ve kayıp faktörü gibi özellikler hakkında bilgiyi kaydeder. Daha sonra bu bilgiler probun arayüzü sayesinde analiz edilir ve dielektrik özellikler hakkındaki bilgileri elde etmemizi sağlar. Başka bir çok dielektrik ölçme yöntemi de litaratürde mevcuttur. Frekans domaini reflektometrisi, zaman domaini reflektometrisi, kapasitif ve indüktif ölçüm yöntemlerinde kullanılmaktadır. Ancak açık uçlu prob yöntemi tercih etmemizin bir çok nedeni varrdır. Bu yöntem diğer ölçüm yöntemlere göre daha az karmaşıktır. Sistemi kurması ve kullanması daha basittir. Ölçülen malzemeye zarar vermediği için hem daha doğru hem de yüksek hassasiyette ölçümler yapmamıza olanak sağlıyor. Kullanılan malzeme de tahribata neden olmaması ölçümlerin de tekrarlanabilirliğine imkan verir. Son olarak açık uçlu prob tekniği geniş frekans aralığında çalışabilir. Bu sayede malzemelerin farklı frekanslarda nasıl elektriksel özellikler gösterdiği incelenebilir.

Yapılan tüm ölçümlerde jelatin fantomlar 500 MHz ile 10 GHz frekans aralığında ve oda sıcaklığında ölçülmüştür.

Ölçüm sonuçlarını yorumlamak ve gerçek dokularla karşılaştırmak için matematiksel yöntemler kullanılması gerekmektedir. Bu çalışmada kullanılan matematiksel yöntem Cole-Cole yöntemidir. Bu yöntem malzemenin frekans bağımlı dielektrik özelliklerini belirlemek için kullanılan yaygın bir yöntemdir. Cole - cole denkleminde dielektrik sabit ve kayıp faktörünü tanımlayan bir kompleks permitivite fonksiyonu vardır. Bu modelle dielektrik malzemenin karışık davranışları da açıklanabilir. Bir sonraki deney olan ısıya bağımlı özelliklerin incelenmesinde de bu yöntem için uygun bir modeldir. Bu model ile sayısal verilere dönüştürülen elektriksel özellikler önceki çalışmalarla ve IFAC web sitesinde mevcut olan gerçek dokuların frekansa bağlı dielektrik özellikleriyle karşılaştırıldı. Hangi yağ yüzdesine sahip fantomların hangi dokuları taklit ettiği belirlendi. Gerçek dokularla benzer elektriklesel özellik gösteren fantomlar belirlendi. Akciğer, karaciğer, meme dokusu ve kan ile benzer özellik gösteren fantomlar ile farklı bir çalışma daha yapıldı. Bu dokuların tercih edlme nedenleri vardır. Meme kanseri en çok rastlanan kanser türlerinden biridir. Karaciğer dokusu üzerinde ise çok fazla termal ablasyon çalışması yapılmış ve bu konuda çokça litaratürde makale mevcuttur. Bu sayede de üretilen fantomların deney sonucunda elde edilen dielektirk özelliklerinin ne kadar doğru olduğunu karşılaştırmak ve ısıya bağımlılığını test etmek için çokça kaynak ve bilgi mevcuttur.

Fantomlar seçildikten sonra dokulardaki ısı artışı sonucunda dielektrik özelliklerin değişimini gözlemlemek için bir farklı bir deney düzeneği hazırlandı. Dokuyu ısıtmak için sıcak su banyosu kullanıldı. Sıcak su banyosuna yerleştirilen fantomlar oda sıcaklığından 50 - 55 dereceye kadar ısıtıldı. Bu sıcaklıkların seçilmesinin temel nedeni bu sıcaklıklardan sonra dokuda meydana gelen protein denatürasyonudur. Doku yüksek ısıya otuz dakikadan uzun süre maruz kalırsa, bu doku da kalıcı hasara neden olur ve geri döndürülemez.

Bu çalışmayı yapmamızın temel amacı jelatin kullanılarak üretilen doku fantomlarının ısıtıldığında elektriksel özelliklerinde ne gibi değişikler olabileceğini anlamaktı. Hazırlanan tüm doku fantomları önce oda sıcaklığında, daha sonra vücut sıcaklığından 55 dereceye kadar tüm sıcaklıklarda açık uçlu koaksiyel prob kullanılarak ölçüldü.

Kullanılan ölçüm düzeneği, Speag marka DAK 3.5mm prob kiti bu prob sayesinde geniş frekans bandında 10 MHz ile 10 GHz frekans aralığında ölçümler yapılmıştır. Bu frekansı aralığı Agilent N5230A marka bir vektör ağ analizörü ile ayarlanmıştır. Her bir fontomun homojenliğini de test etmek için farklı üç noktadan ölçümler alınıp bu ölçümlerin ortalamaları hesaplanmıştır. Oda sıcaklığındaki ölçümler tamamlandıktan sonra NUVE sıcak su havuzu kullanılarak tüm fantomlar ısıtılmış ve ısıtma esnasında her bir derece de bir fantomlardan üçer ölçüm alınarak sonuçlar kaydedilmiştir. Tüm fantomlar 50 derece ye kadar ısıtılıp sonuçlar kaydedildikten sonra sıcak su havuzu kapatılarak tekrar oda sıcaklığına dönülene kadar yine her bir derece de bir soğuma verileri de kayıt altına alınmıştır.

Elde edilen tüm sonuçlardan bağıl dielektrik değerleri ve iletkilik değerleri hesaplanmak için bir matlab kodu kullanıldı. Yine Cole-Cole denklemlerinden yararlanıldı ve ikinci dereceden bir polinom kullanarak denklem sıcaklığa uygun hale getirilmiştir. Tüm sonuçlar grifikler haline getirilerek litaratüde bulunan ısıya bağımlı dielektrik özelliklerle karşılaştırıldı ve hata oranları hesaplandı.

Deneyler sonucunda elde edilen tüm bulgular, jelatin fantomlarındaki yağın doku taklidinde başarılı materyaller olduğunu gösterdi. Karşılaştırmalar sonucunda fantomların dielektrik özelliklerinin gerçek dokularla uyumlu olduğu ve ısıtma ve soğutma işlemleri sonucunda hala dokuların dielektrik özelliklerine benzer özellikler gösterdikleri kanıtlandı.

1. INTRODUCTION

Since the early twentieth century, scientists have been studying the dielectric characteristics of biological tissues [1]. The use of electromagnetic energy for medical imaging and therapy, as well as the rapid growth of personal devices that emit electromagnetic energy at microwave frequencies, have increased research into how electromagnetic waves interact with biological tissues, particularly at microwave frequencies [2]. Essentially, the interactions and propagation of electromagnetic fields inside biological tissues are governed by the dielectric characteristics [1]. The dielectric properties of biological tissues have been tested by various researchers at different frequencies and different temperatures, but most of these studies were at or below physiological temperature about 37 °C. However, due to the rapid increase in cancer cases in recent years, treating tissues with microwave tissue heating, including hyperthermia and thermal ablation, by raising them to temperatures higher than 40 °C has been the subject of clinical use and various research. There is also work with this method to treat various diseases, including cardiac arrhythmias, Parkinson's disease, hyperopia, hyperplasia, and others [3]. Because these treatment procedures occur at temperatures beyond room temperature, the resulting change in tissue dielectric properties must be considered. Electrical tissue qualities have an immediate effect on the absorption of electromagnetic energy, which results in a heating generation; these features are thus critical to early-stage and clinical uses utilizing electromagnetic waves for heating, as well as thermal treatments in total because dielectric characteristic changes following heating will influence tissue distribution of temperatures and the ensuing thermal harm [4]. As a result, there is a need for biological phantoms that mimic the dielectric properties of tissues at these high frequencies and different heat rates. A number of phantoms have been created for this purpose. According to the base component, these materials can be classified into different types. One of these classifications is based on the main material used during the production of the phantom, and oil-in-gelatin phantoms are one of the subspecies of this classification. In addition to having similar dielectric properties with tissues, the produced phantoms should also have qualities such as safety, low cost, simplicity in preparation, and long life [5]. Gelatin-in-oil phantoms are widely regarded as one of the most preferred types of phantoms due to they provide these properties. Despite the various approaches available, the open-ended coaxial probe is the most commonly used technique for determining the dielectric characteristics of biological tissues because it needs non-invasive functioning, simple preparation of the sample, and effortless temperature control. The relative conductivity and permittivity coefficients of the oil-in-gelatin phantoms prepared to determine the temperature-dependent variable dielectric properties were measured using an open-ended coaxial probe approach. Dielectric properties are not directly measurable characteristics. Therefore, the data collected from measurement devices are converted into dielectric properties. The fact that the dielectric properties of tissues vary with frequency has allowed for their expression through mathematical modeling. The model developed by Debye to investigate the frequency-dependent dielectric behavior of polar molecules has taken on different forms in subsequent studies, and the expression called the Cole-Cole equation has been frequently used in the literature to represent the dielectric properties of biological tissues [6,7]. In this manner, we can numerically interpret the temperature-dependent dielectric properties of oil phantoms in the gelatin we produce and obtain precise information on the effect of changing temperatures on these dielectric properties.

A thesis study was conducted, which involved producing phantoms resembling various human body tissues by altering the fat content within gelatin. These phantoms were then heated using a hot water bath, raising the temperature from approximately 22 degrees Celsius to 50 degrees Celsius, and the corresponding changes in dielectric properties were recorded. The dielectric properties obtained were compared with previous studies and the dielectric properties of real tissues found in the IFAC website [8], focusing on the analysis of the variation of dielectric properties with temperature.

2. LITERATURE REVIEW

2.1 Dielectric Properties

In the past century, a wide range of measurement methods has been used to extensively explore the dielectric characteristics of biological tissues over diverse frequency ranges [9]–[12]. Understanding how electromagnetic waves interact with and travel through biological tissues depends critically on these characteristics. An accurate understanding of dielectric characteristics is useful in many fields, including biology, agriculture and food production, and medical applications in healthcare.

Characterizing and controlling human exposure to electromagnetic fields is one important application. Assessing the potential health concerns linked to electromagnetic radiation exposure involves understanding the dielectric characteristics of tissues. Setting safety standards and limitations for electromagnetic systems and devices is made easier by this information [2] Characterizing and controlling human exposure to electromagnetic fields is one important application. Assessing the potential health concerns linked to electromagnetic radiation exposure involves understanding the dielectric characteristics of tissues. Setting safety standards and limitations for electromagnetic systems and devices is made easier by this information. In addition, the dielectric characteristics of biological tissues have aided in the development of microwave-frequency cancer detection and therapy systems. These features have been used by researchers to develop novel procedures such as microwave thermotherapy, which selectively targets and eliminates cancer cells while causing minimal damage to healthy tissues [13]–[18]. In general, research and knowledge of dielectric characteristics in biological tissues have far-reaching consequences, ranging from consumer safety to breakthroughs in various fields such as agriculture and healthcare [1]. Because of its non-destructive nature and capacity to provide broadband measurements in both in vivo and ex vivo environments, the open-ended coaxial probe has grown in popularity since the 1980s [19,20]. Moreover, investigators examined the dielectric characteristics of biological tissues, considering parameters such as percentage of water, medical condition (healthy or tumor), and whether measurements were taken in vivo or ex vivo. Major advances in dielectric property measurements of animal and human tissues were made in 1996, in both in vivo and ex vivo conditions [21]–[23].

In these instances, measurements are often taken at room temperature. However, direct contact with the test material is required in vivo research employing the open-ended coaxial probe method and other measuring techniques, necessitating a lower measurement temperature than normal body temperature. Furthermore, certain treatment steps, such as hyperthermia and ablation, entail notably greater heat than ambient temperature, necessitating consideration of changes in tissue dielectric characteristics. Schwan and Li [11], measured the dielectric characteristics of biological tissues at multiple frequencies and temperatures in 1953 and presented their findings in terms of linear temperature coefficients. These coefficients indicate the percentage change in conductivity or conductivity per degree Celsius [1].

Numerous studies have been conducted to investigate the dielectric properties of various types of tissues, and their results have been published. These experiments have utilized different frequency ranges and varying temperature values better to understand the influence of these parameters on dielectric properties. Table 1 provides a chronological summary of different studies conducted for dielectric measurements, including the preferred frequency range and temperature coefficients. [1].

The calculated temperature coefficients were not included in the investigations that were undertaken; instead, they concentrated on discrete frequencies between 915 MHz and 2.45 GHz. The use of linear discrete-frequency temperature coefficients is impractical for ultra-wideband applications. This is due to the requirement that temperature coefficients be supplied for each frequency and relevant temperature range. Hence, this thesis presents a systematic measurement approach to assess the temperature dependence of dielectric properties across a broad frequency range of 0.5–10 GHz. The Cole-Cole parameters were employed to characterize the temperature-related changes in dielectric properties over wide bandwidths. This

Table 2.1 : A chronological review of the information on temperature-dependent dielectric characteristics [1].

References	Tissue Type	Frequency Range	Temperature coefficient (%°C $^{-1}$)
[12]	Several tissues	50, 200, 400, 900 MHz	See reference
[24]	Biological tissues	Microwave	$\frac{\Delta\alpha}{\alpha} = 2, \frac{\Delta\varepsilon}{\varepsilon} = -0.5$
[25]	Brain	< 0.1 GHz < 2 GHz 7 GHz	$\frac{\Delta\alpha}{\alpha} = 2, \frac{\Delta\varepsilon}{\varepsilon} = 2$ $\frac{\Delta\alpha}{\alpha} = 2, \frac{\Delta\varepsilon}{\varepsilon} = small$ $\frac{\Delta\alpha}{\alpha} = -1, \frac{\Delta\varepsilon}{\varepsilon} = small$
[26]	Biological tissues	Microwave	$\frac{\Delta\alpha}{\alpha} = 1to2, \frac{\Delta\varepsilon}{\varepsilon} = -0.3to2$
[27]	Biological tissues	Microwave	≈ 2
[28]	Muscle fibres	0.1 - 2.2 - 9.5 GHz	$\frac{\Delta\alpha}{\alpha} = 2to-2, \frac{\Delta\varepsilon}{\varepsilon} = small$
[29]	Myocardium	0.2 -1.1 -2.45GHz 3 - 4 - 5 - 6 GHz	see referance
[30]	Bovine liver	915 MHz	$\frac{\Delta\alpha}{\alpha} = 1.82, \frac{\Delta\varepsilon}{\varepsilon} = -1.3$
[31]	Bovine and Porcine liver	0.3 - 3 GHz	B=$\frac{\Delta\alpha}{\alpha} = 2, \frac{\Delta\varepsilon}{\varepsilon} = -0.04$ P= $\frac{\Delta\alpha}{\alpha} = 1.1, \frac{\Delta\varepsilon}{\varepsilon} = -0.17$

method successfully determined the dielectric properties of different tissue phantoms within the room temperature range of 50°C, encompassing frequencies from 500 MHz to 10 GHz.

2.2 Tissue Mimicking Phantom

Synthetic fluids called "tissue-mimicking-phantoms" can imitate the characteristics of a particular human tissue [32], [33]. Phantoms are widely used in various medical sectors for tissue examination and evaluation of new tools. The use of phantoms in healthcare began soon after the discovery of X-rays in 1896. Because of the high radiation levels involved, scientists began working on materials that could resemble human tissues. Water was originally the fundamental component of early phantoms and is still a good option.

In the 1960s, Alderson et al. [34] developed a more advanced dosimetry phantom with a human skeleton within the fundamental material.

During the 1970s, phantom development evolved to include numerous imaging methods, such as computed tomography and mammography, and in 1989s Griffiths et al. [35] produced a phantom of salt and water to be used in Electrical Impedance Tomography [36].

Comparable electrical characteristics among human tissue and tissue-mimicking phantoms are required. Several forms of tissue-mimicking solutions are used, each using a different core material. These consist of hydrogels and polyvinyl alcohol. (PVA) cryo-hydrogels, polyacrylamide-based gels, gelatin-based phantoms, oil-in-gelatin phantoms, agar-based phantoms, agarose-based phantoms, plastic-based polyvinyl chloride plastisol. (PVCP) phantoms, and magnesium silicate-based phantoms [37], [38], [39], [40].

The selection procedure becomes essential in the search for acceptable phantom materials that properly imitate the properties of real tissues. It is necessary to take into account factors like radiological, electrical, and mathematical qualities. Gelatin, agar, and agarose are suggested as materials for imitating tissue electrical properties by Kandadai et al. These materials are favored because they are affordable, simple to manufacture, readily available, and stable [41].

Another type of substance utilized for phantom fabrication is polyacrylamide gel, first developed in 1984 by Bini et al. and further studied in 1988 by Andreuccetti et al.

These materials' optical transparency and gel-like mechanical characteristics make them desirable. Their short shelf life, which can range from a few hours when exposed to air to a few weeks when kept in an airtight container, is a downside [2], [42].

Surowiec et al. in 1992, McCann et al., Davidson and Sherar, and other researchers in 2003 were more recent researchers to modify these materials. However, the processes used to create these materials are intricate, sometimes calling for using chemicals that might be difficult to come by.

Gelatin-based phantoms are chosen after analyzing multiple research articles and weighing the pros and cons of different alternatives because they have the advantages of being readily available, being simple to manufacture, and being easy to vary electrical conductivity. Different amounts of gelatin are employed to make materials with various dielectric characteristics. This formulation, however, does not allow for persistent heterogeneous phantoms since the gelatin content is adjusted to obtain variable dielectric characteristics.

Nguyen et al. [43] introduced the first microwave phantoms with thermal tissue characteristics, specifically for microwave hyperthermia operations. Only a few phantom designs that accurately simulate the temperature-dependent permeability of different tissue types across a broad frequency range have been published in the literature [5].

This work aims to produce gelatin-based tissue-mimicking phantoms and to have these phantoms in a structure similar to the dielectric properties of body tissues. In this way, they are designed to investigate temperature-dependent dielectric properties. The measurements of these phantoms, which we produced in the following chapters, with the help of an open-ended coaxial probe and the graphs of their dielectric properties, are reported.

3. BACKGROUND

3.1 Dielectric Properties of Biological Tissues

The use of electromagnetic energy for medical imaging and therapy, as well as the rapid growth of personal devices that emit electromagnetic energy at microwave frequencies, have increased research into how electromagnetic waves interact with biological tissues, particularly at microwave frequencies [2]. Essentially, the interactions and propagation of electromagnetic fields inside biological tissues are governed by dielectric characteristics.

The nature of the physical state of water in biological systems and the fundamental physiological distinctions between normal and malignant tissue might both be better understood at the molecular level with the help of dielectric research. According to several researchs, the relative permittivity and electrical conductivity frequency fluctuations are taken into account while dealing with tissues' dielectric characteristics [44].

Dielectric properties are not directly measurable characteristics. Therefore, the data collected from measurement devices are converted into dielectric properties. The fact that the dielectric properties of tissues vary with frequency has allowed for their expression through mathematical modeling. The model developed by Debye to investigate the frequency-dependent dielectric behavior of polar molecules has taken on different forms in subsequent studies, and the expression called the Cole-Cole equation has been frequently used in the literature to represent the dielectric properties of biological tissues [6,7].

3.1.1 Basics of Tissue Dielectric Properties

Scientists developed several mathematical models to describe the characteristic behavior of biological dielectrics. For illustrating complicated relative permeability, Debye [10], Cole-Cole [11], and Cole-Davidson [12] equations are frequently employed. The

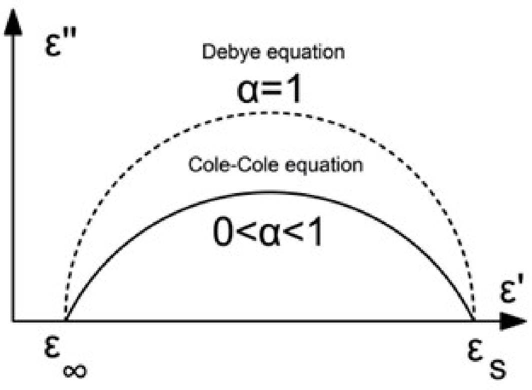


Figure 3.1 : Diagrams of Cole-Cole and Debye Equation.

cole-Cole model is frequently used to represent the temperature-dependent dielectric characteristics of biological tissues. The Cole-Cole model's coefficient parameter, which stretches dielectric relaxation, is the cause of this. Instead of using alternative approaches, this results in calculations that are more precise when expressing the dielectric relaxation of biological tissues. In Figure 3.1, the advantage of the exponent parameter is depicted.

The temperature-dependent dielectric properties are described by the complex relative permittivity

$$\varepsilon(\omega,\vartheta) = \varepsilon'(\omega,\vartheta) - i\varepsilon''(\omega,\vartheta) \tag{3.1}$$

and the effective conductivity as shown in equation 3.1.

$$\sigma(\omega,\vartheta) = \omega\varepsilon_0\varepsilon''(\omega,\vartheta) \tag{3.2}$$

Here the ε' is symbolized the relative permittivity reel component, ε'' is symbolized the imaginary component, ε_0 dielectric loss factor, ω the angular frequency and ϑ is symbolized the e temperature.

3.1.2 Temperature Dependent Cole-Cole Equation

The three relaxation areas in the low, middle, and high frequency ranges define the frequency-dependent dielectric properties of tissue [30]. Gabriel developed a four-pole Cole-Cole model to represent the spectrum from 10 Hz to 100 GHz [31-10.3390@s19071707].

$$\varepsilon(\omega,\vartheta)=\varepsilon_\infty(\vartheta)+\frac{\Delta\varepsilon_1(\vartheta)-\varepsilon_\infty}{1+(i\omega\tau_1\vartheta)^{1-\alpha_1}}+\frac{\Delta\varepsilon_2(\vartheta)-\varepsilon_\infty}{1+(i\omega\tau_2\vartheta))^{1-\alpha_2}}+\frac{\sigma_s(\vartheta)}{i\omega\varepsilon_0} \tag{3.3}$$

Here the ε_∞ is symbolizes the permittivity at high frequencies, $\Delta\varepsilon_{1,2}$ are are the dispersion amplitude, $\tau_{1,2}$ the corresponding relaxation times, $\alpha_{1,2}$ the empirical distribution components and σ_s is symbolizes the static conductivity.

To match the Cole-Cole equations to the experimental data at each temperature that matches Equation (3), we utilize the Levenberg-Marquart method. For each tissue, $\alpha_{1,2}$ are assigned to a constant number. Initially, by reducing the mean absolute error throughout the desired frequency range, we establish the Cole-Cole variables to suit the real component of the complex permittivity. In the next step, we fit the temperature dependence of the Cole-Cole parameters using a second-order polynomial, which is also recommended by Lazebnik [1]. Lastly, it is possible to calculate the temperature-dependent dielectric characteristics by

$$\begin{aligned}
\varepsilon_{\infty,fit}(\vartheta) &= A_1\vartheta^2+B_1\vartheta+C_1\\
\Delta\varepsilon_{1,fit}(\vartheta) &= A_2\vartheta^2+B_2\vartheta+C_2\\
\tau_{1,fit}(\vartheta) &= A_3\vartheta^2+B_3\vartheta+C_3\\
\Delta\varepsilon_{2,fit}(\vartheta) &= A_4\vartheta^2+B_4\vartheta+C_4\\
\tau_{2,fit}(\vartheta) &= A_5\vartheta^2+B_5\vartheta+C_5\\
\sigma_{s,fit}(\vartheta) &= A_6\vartheta^2+B_6\vartheta+C_6
\end{aligned}$$

The following parts provide the coefficients A, B, and Cn (n = 1,2,3,4,5,6) for the various tissues. Lastly, it is possible to calculate the temperature-dependent dielectric characteristics by

$$\begin{aligned}
\underline{\varepsilon}_{fit}(\omega,\vartheta) &= \varepsilon'_{fit}(\omega,\vartheta)-i\varepsilon''_{fit}(\omega,\vartheta)\\
&= \varepsilon_{\infty,fit}(\vartheta)+\frac{\Delta\varepsilon_{1.fit}(\vartheta)}{1+(i\omega\tau_{1,fit}(\vartheta))^{1-\alpha_1}}+\frac{\Delta\varepsilon_{2,fit}(\vartheta)}{1+(i\omega\tau_{2,fit}(\vartheta))^{1-\alpha_2}}+\frac{\sigma_{s,fit}(\vartheta)}{i\omega\varepsilon_0}
\end{aligned} \tag{3.4}$$

3.1.3 Tissue Dielectric Property Measurement Method

Numerous investigations on the dielectric characteristics of biological tissues have been carried out over time, with major improvements in measuring devices and methods. This research tried to describe how tissues behaved dielectrically with respect to their physiological characteristics. One method entailed comparing the dielectric characteristics of tissues in vivo and ex vivo by looking at how they depended on the level of water at microwave frequencies. Scientists also examined the distinctions between normal tissues and those with differences. Ex vivo or animal measurements were utilized when required, while in vivo measurements on people were preferred wherever practical. Gabriel et al.'s measurements and data collecting immediately established themselves as the industry standard for describing the dielectric characteristics of biological tissues. The established findings, which are now considered to be the norm for biological tissues, were first made publicly available as open source on the Federal Communications Commission (FCC) page and then on the Ifac.cnr.it page of the Italian National Research Council (CNR) [23].

In the subsequent year, Lazebnik et al. conducted research on the dielectric properties of breast tissue, aiming to assess the feasibility of microwave imaging for early tumor detection. According to the study, the difference in dielectric characteristics between normal tissue and malignant or cancer tissue, as seen in the data that was gathered, might not be accurate enough for clinical detection utilizing this method.

Meaney et al. and Porter et al. looked into the dielectric characteristics of heterogeneous biological tissues at the same time. They especially looked at frequently used commercial dielectric probes and assessed how the composition of the tissue being tested affected the observed dielectric characteristics [45]. The probe technology is the most practical way of measuring the dielectric characteristics of biological tissue at microwave wavelengths. In the next section open-ended prob technique will be more explained.

3.1.4 Open-Ended Coaxial Probe Method and Calibration

In research, the open-ended coaxial probe technique is frequently used to measure materials with high dielectric characteristics and complicated permittivity. This approach enables broadband measurements and gives sample form and size flexibility, making it appropriate for a wide range of uses.

The open-ended probe method has a number of benefits. The ability to monitor frequencies up to 50 GHz is provided by its first feature, wideband measurements. Furthermore, because the probes may be employed with ease in liquids and semi-solid materials, this approach does not need sample preparation. However, there are certain disadvantages associated with this technique. The rather large measurement error, which can reach %5 [14], is a problem. The approach also shows poorly reproducible [22]. The network analyzer has to be sufficiently warmed up before the experiment and the equipment must be calibrated correctly to provide reliable measurements [46]. The coefficient of reflection is measured using a coaxial probe attached to a network analyzer to continue the measurements. Following that, an algorithm calculates the material's dielectric characteristics using the reflection value.

In this study, the DAK 3.5mm probe kit and Agilent N5230A PNA L network analyzer be used for dielectric measurement as shown in Figure 3.2 and the frequency range in this search was chosen to be 500 MHz to 10 GHz. To ensure accurate measurements, the DAK 3.5 mm probe was initially calibrated before conducting any measurements. To address the directivity, tracking, and source match errors that may arise in a reflection measurement, a three-term calibration approach is employed. This calibration method involves measuring three widely recognized standards to determine and correct for these error terms. These standards are open, short, load (O-S-L). Open is the measurement of air when the probe is empty. The short is the probe covered and measured using a blocker. Load is the measurement made by using deionized water and taking into account the temperature of the water. After these three standards are measured, the calibration is completed and the desired items can be measured.

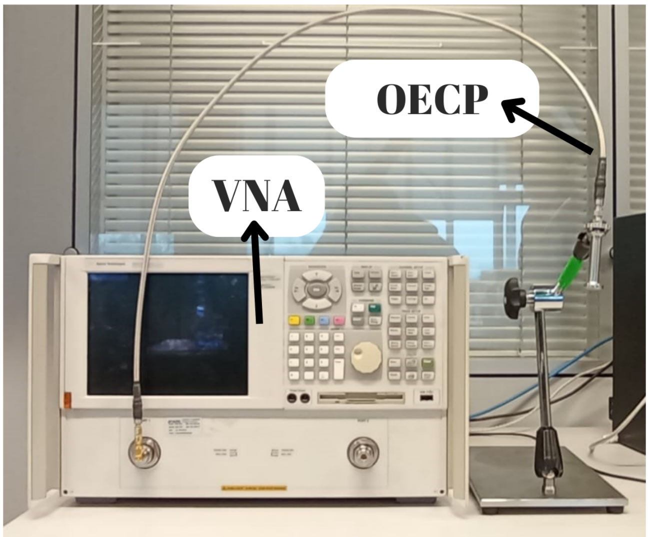


Figure 3.2 : Dielectric measurement setup, Open-ended coaxial probe (OECP), Vector network analyzer (VNA).

3.2 Preparation of Gelatin-Based Tissue Mimicking Phantoms

Gelatin-based phantoms are chosen after analyzing multiple research articles and weighing the pros and cons of different alternatives because they have the advantages of being readily available, being simple to manufacture, and being easy to vary electrical conductivity.

Phantom samples created utilizing gelatin were examined in the literature. The study considered various factors, including the accessibility of the materials employed, production expenses, simplicity of implementation, and applicability across diverse tissue experiments. An oil-in-gelatin phantom, which fulfills these criteria, was produced using the preparation steps recommended by Lazebnik [2].

Initially, gelatin and sunflower oil are mixed in a beaker. After the mixture is heated up to 90 °C in a hot bath and homogeneous, it is cooled to 50 °C and the desired amount of the mixture is taken into another container and then Fairy brand detergent is added and mixed. Thanks to the mixing process, an even appearance is obtained everywhere. Afterward, formaldehyde is added and mixing is continued and it is allowed to cool down to 34 °C. It takes one day for the formaldehyde solution to chemically bind to the gelatin and solidify the phantoms.

Table 3.1 : Quantities of materials added to the phantom. F.dehyde: Formaldehyde.

%Oil Rate	Taken Mixture (ml)	Add Oil (ml)	Dish-washing (0.056 ml per ml of oil)	F.dehyde (0.0108 gr per ml of mix)
% 5	95 ml	5 ml	0.28 ml	1.026 gr
% 15	85 ml	15 ml	0.84 ml	0.918 gr
% 35	65 ml	35 ml	1.96 ml	0.702 gr
% 55	45 ml	55 ml	3.08 ml	0.486 gr

1. The hot water jacket is adjusted to 90 °C, filled with distilled water up to the reference point, and placed in the gelatin-distilled water mixture we prepared.

2. The mixture, which is heated up to approximately 90 °C, has a homogeneous appearance. If there are air bubbles in the mixture taken from the hot water jacket, they are removed, and it stays to reach a temperature of 50 °C.

3. Sunflower oil is added to another beaker, and the beaker is covered with a stretch film to prevent water vapor from getting into the beaker, and heated up to 50 °C in the hot water jacket.

4. In the gelatin mixture that becomes homogeneous, the desired amount is taken heated sunflower oil is added and mixing is continued.

5. The emission is mixed until homogeneous and cooled to 40 °C.

6. While continuing to mix, 0.056 ml of dish-washing liquid is drawn per ml of oil using a syringe and added to the beaker.

7. Then 0.0108gr per ml of gelatin solution was added to the mixture.

8. The formaldehyde solution is added to the mixture with the help of a syringe and mixed.

9. After all the materials to be sieved are finished, mixing is continued until the entire mixture reaches approximately 34 °C.

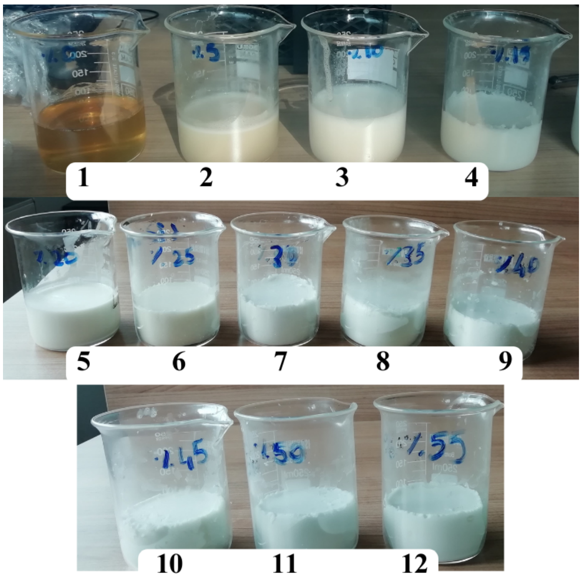


Figure 3.3 : The oil ratios of the prepared phantoms are from 1 to 12, respectively: %0, %5, %10, %15, %20, %25, %30, %40, %45, %50, %55.

10. The only color phantom formed as a result of the processes becomes an almost white color in proportion to the increasing oil rate.

11. It takes approximately five days for the formaldehyde solution to chemically bond with the gelatin and for the phantom to be ready for measurement.

In Table 3.1, the details of the application of sunflower oil, dishwashing liquid, gelatin, and formaldehyde at certain oil ratios, as mentioned in the phantom preparation stages, and the calculated values of the materials used are listed. In Figure 3.3, there is a collective picture of all phantoms with different oil values. As mentioned while describing the stages, the color of the phantom obtained approached white as the oil content added to the gelatin mixture increased.

4. MEASUREMENT OF DIELECTRIC PROPERTIES OF A TISSUE-MIMIC GELATIN-BASED PHANTOM WITH A COAXIAL PROBE

4.1 Introduction

Biological tissues exhibit distinct dielectric properties due to the presence of polar molecules, particularly water. These properties play a crucial role in understanding the behavior of tissues when exposed to microwave frequencies. Analyzing these behaviors can provide insights into the health status of the tissue, including whether it is healthy or cancerous.

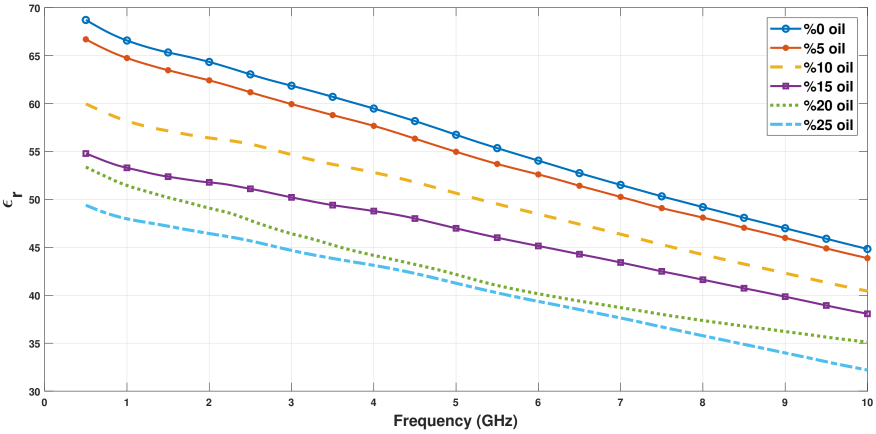
Nevertheless, it is not always feasible to extract tissues from the body for ex-vivo experiments to characterize their dielectric properties. To overcome this limitation, scientists have developed phantom materials that possess similar electrical properties to those of actual tissues. In laboratory settings, coaxial probes are commonly employed as a measurement technique to determine the dielectric properties of these prepared phantoms. Coaxial probes offer numerous advantages, including simplified sample preparation, the ability to measure across a wide range of frequencies, and ease and speed of measurement.

4.2 Materials and Methods

The amount of gelatin used, the proportion of sunflower structure and the amount of formaldehyde added while preparing tissue-imitating gelatin-based phantoms are mentioned in detail in section 3. The phantoms prepared in this study were measured using a 3.5 mm Dak probe kit and Agilent N5230A PNA-L network analyzer. The 3.5 mm Min Probe can measure in wide frequency ranges from 200 MHz to 20 GHz. The measurement range was chosen in the range of 500MHz to 10GHz due to the compatibility with the literature comparisons to be made later. Thanks to the software of the open-ended Dak 3.5mm probe, the dielectric properties can be converted into numerical values. In this way, S parameters and permittivity values were calculated and recorded. These values were converted into dielectric and relative permittivity graphs with the help of MATLAB.

4.3 Results and Discussion

In this thesis, measurements were conducted using 12 phantom OECP kits prepared with oil ratios ranging from %0 to %55. The permittivity and conductivity values of all measured phantoms were examined. For more accurate results, three measurements were taken from the surface of each phantom, and the average of these measurements was calculated. The obtained data was transformed into electrical properties using Matlab.



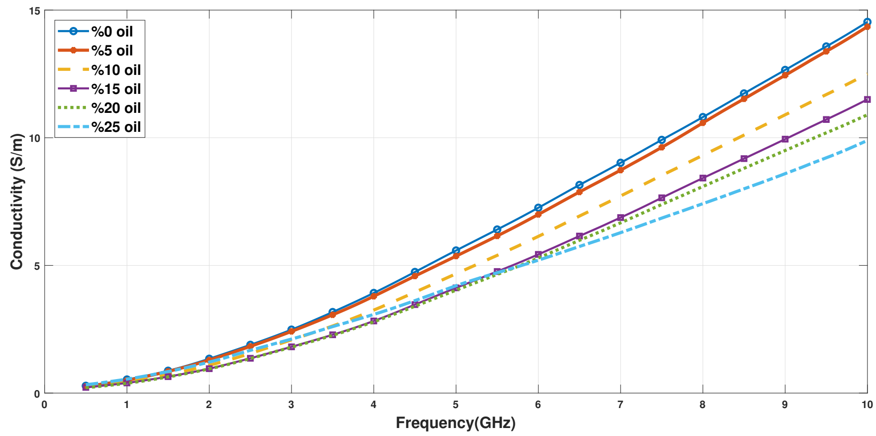


Figure 4.1 : Phantoms with %0, %5, %10, %15, %20, %25 oil ratio (A) relative dielectric constants and (B) conductivity values change the frequency response.

As seen in Figure 4.1, it is evident that the oil ratio has significant effects on the phantoms, as detailed. The measurements revealed that as the fat percentage increased

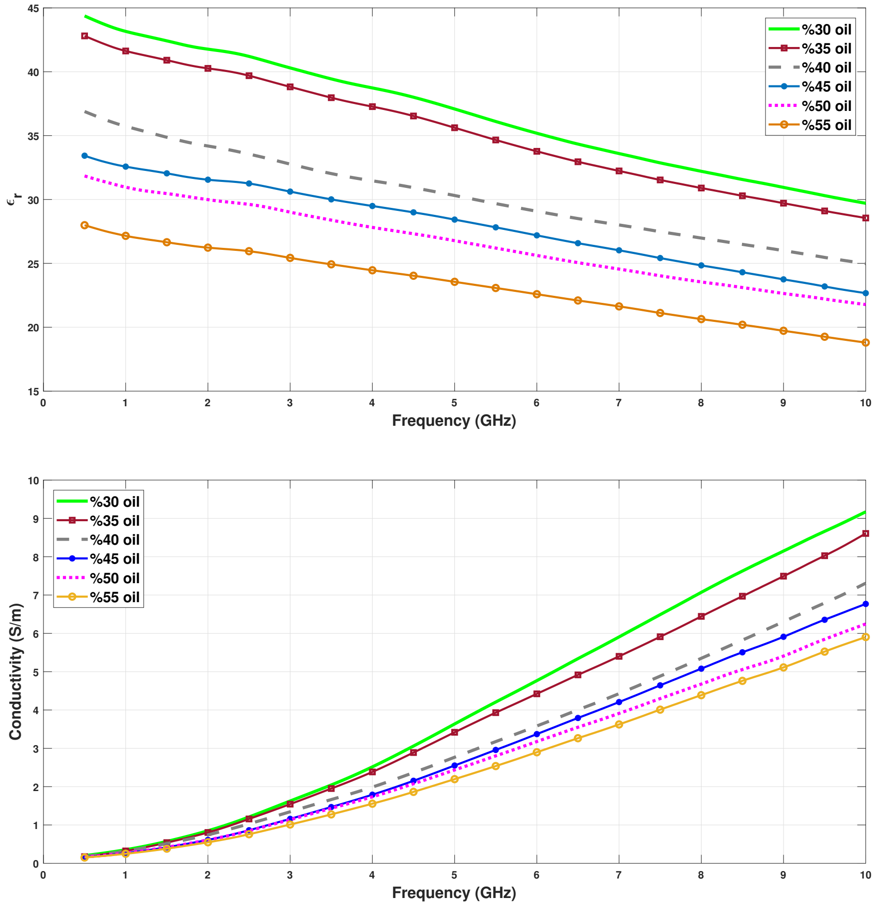


Figure 4.2 : Phantoms with %30, %35, %40, %45, %50, %55 oil ratio (A) relative dielectric constants and (B) conductivity values change the frequency response.

for the phantoms, there was a decrease in the relative permittivity and conductivity values due to the low relative dielectric and conductivity properties of oil.

5. TEMPERATURE DEPENDED ON DIELECTRIC CHARACTERIZATION OF BIOLOGICAL TISSUE PHANTOMS USING AN OPEN-ENDED PROBE

5.0.1 Introduction

For many years, the dielectric characteristics of different tissues—that is, their electrical conductivity and permittivity—have been evaluated at body temperature [21], [12]. Most measuring modalities such as open-ended coaxial probes need close contact with the material being tested, even during in vivo research, measurement is usually made by lowering the temperature to levels close to body temperature. However, some treatment methods like ablation and hyperthermia occur at temperatures much higher than room temperature, and the resulting alteration in the tissue's dielectric characteristics needs to be considered [1]. In subsequent studies, researchers the dielectric characteristics of biological tissues at numerous temperatures and discrete frequencies. They then reported their findings using linear temperature coefficients, which are expressed as the percentage change in permittivity or conductivity per °C [11]. The tissue's effective conductivity and dielectric permittivity are strongly temperature-dependent, particularly in reaction to drying and water vapor [1], [47], [48]. Protein coagulation causes dead cells in tissue exposed to over 50 °C. At forty to forty-five °C, permanent harm to cells occurs after exposure for more than thirty minutes, but at sixty-degree Celsius, protein denaturation happens quickly [49], [50]. The aim of our study was to investigate how tissue phantoms made using gelatin responded to heat. The construction of these phantoms was detailed in Chapter 3. Various tissue mimics were produced following the steps outlined in Lazebnik's article. These tissues included liver tissue, blood, lung, and breast tissue. Initially, the dielectric properties of these fabricated tissues at room temperature were measured. Subsequently, the tissues were heated up to 50 degrees Celsius using a water bath, and changes in their dielectric properties were recorded. After the heating process was completed, the tissues were cooled back to room temperature, and dielectric properties were recorded again. We performed the same procedures for all tissues and compared the results with real tissues by plotting them into graphs. This thesis aimed to investigate the changes in tissue dielectric properties with heat, such as those encountered in procedures like ablation for cancer treatment, and to observe how well the tissues returned to their original properties after the procedure.

5.0.2 Materials and Methods

We prepared a total of 12 phantoms ranging from %0 fat content to % 55 fat content. The dielectric properties of all phantoms were measured using an N5230A PNA Series Network Analyzer and a DAK open ended coaxial dielectric probe kit and thermometer. By comparing the dielectric properties of all phantoms with those of real tissue, we identified four phantoms that exhibited dielectric properties consistent with four different types of tissues.

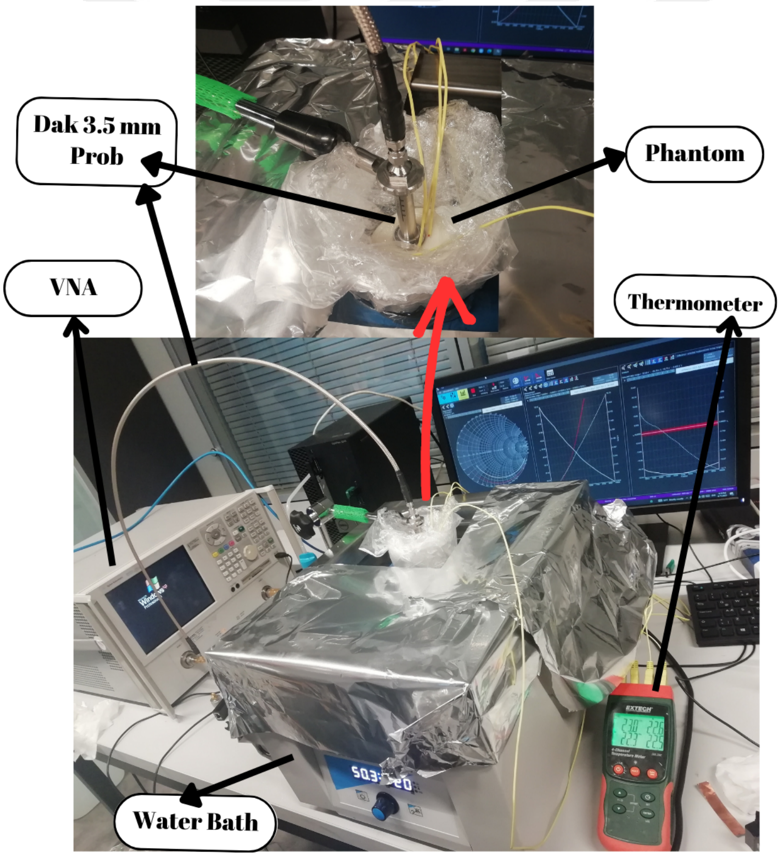


Figure 5.1 : Temperature Depended Dielectric Characterization Measurement Setup.

5.0.3 Results and Discussion

The phantoms, whose dielectric properties were measured and converted into numerical data using Matlab, were compared with the data available in IFAC, and phantoms showing similar properties to real tissues were identified. Subsequently, another study was conducted. The first experiments were conducted on liver tissue phantom, which has been extensively studied in the literature and is readily available as a real tissue sample.

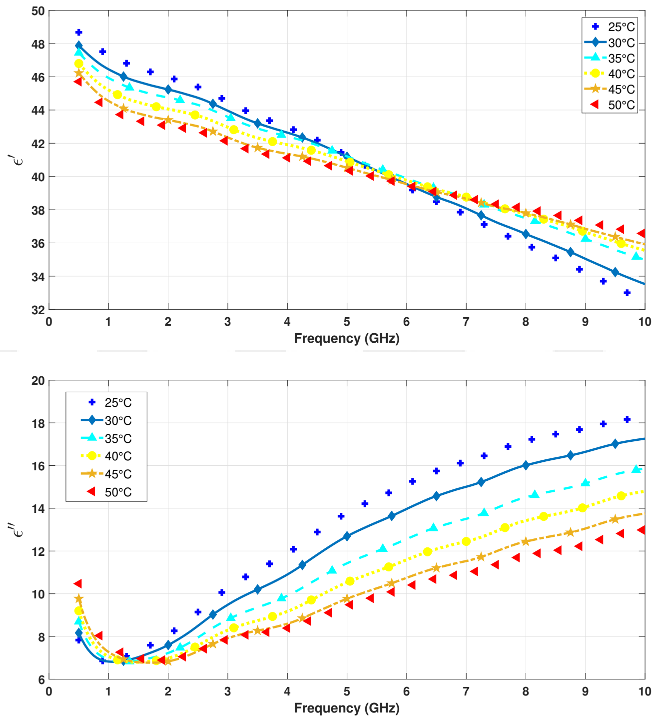


Figure 5.2 : Mean of measured (a) relative permittivity and (b) dielectric loss of liver mimicking phantom as a function of frequency at different temperatures, gathered during heating-cooling cycles .

The phantom produced with a %30 oil ratio was measured using a vector network analyzer and a DAK coaxial probe. Following a comparison between the data and the electrical properties of actual liver tissue, a significant level of resemblance was noted. The liver phantom, which has been demonstrated to accurately replicate actual tissue, was subsequently positioned within the experimental arrangement specifically devised to assess the temperature dependence of dielectric characteristics, as a component of an additional study.

Table 5.1 : Temperature coefficients of third order polynomial fit to the temperature-dependent three-pole Cole-Cole parameters of Liver mimicking phantom

Parameters	A (K^{-3})	B(K^{-2})	C(K^{-1})	D	Adjusted R-Square Error
ε_∞	0,20624	-0,04456	2,26853	-26,0884	0,9769
ε_{s_1}	0,3536 $\cdot 10^{-3}$	-0.0396	1.3942	44.867	0.991
τ_1	-0.2386 (fs)	23.836 (fs)	-0.8764 (ps)	18.928 ps	0.984
α_1	7.5138$\cdot 10^{-6}$	-0.7961$\cdot 10^{-3}$	0.0257	-0.2317	0.972
ε_{s_2}	0.0173	-1.3035	25.348	1349.2	0.662
τ_2	0.8111(ps)	-2.1585(ns)	0.1519(μs)	0.44538μs	0.674
α_2	-9.8622 $\cdot 10^{-6}$	0.0010	-0.0376	0.9002	0.870
σ	-6.7682 (muS)	0.9276(mS)	-0.0353(S)	0.4112	0.993

The phantoms, placed in a water bath, were heated from room temperature to 55 degrees Celsius, and measurements were taken from the phantoms at each degree increment. Figure 5.2 presents the results of the measurements, showing the values of relative permittivity and dielectric loss. These values were averaged at intervals of five degrees.

As expected, temperature increases resulted in decreases in the epsilon prime values (ε'), relative permittivity, of the phantoms. The decline may be attributed to several sources. For example, the rise in conductivity as temperature increases or the enhanced motion of atoms within the material caused by heat could result in a decrease in the dielectric constant. As a result, this leads to a reduction in relative permittivity. After the desired temperature is reached, the water bath is deactivated, and the heating process is stopped. Measurements are ongoing as the liver phantom cools down. As anticipated, when the temperature of the phantom recovers to room temperature, the relative permittivity value starts to increase once more.

As seen, there is a crossover at 8 GHz in all heating-cooling graphs. The liver mimicking phantom's temperature profile functions similarly to that of the blood tissue mimicking material.

At lower frequencies, the real component of the complex relative permittivity value decreases as temperature rises; at higher frequencies, on the other hand, the real part of the complex relative permittivity value increases as temperature rises. In terms

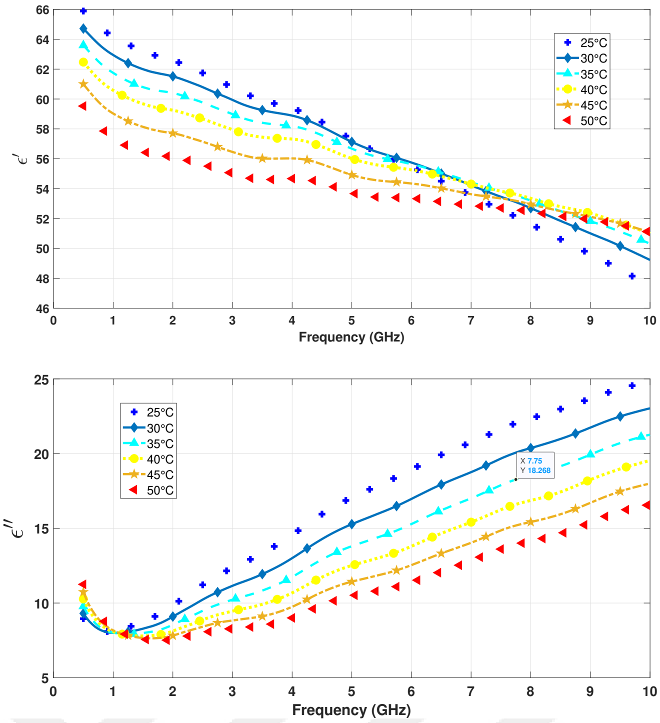


Figure 5.3 : Mean of measured (a) relative permittivity and (b) dielectric loss of blood mimicking phantom as a function of frequency at different temperatures, gathered during heating-cooling cycles .

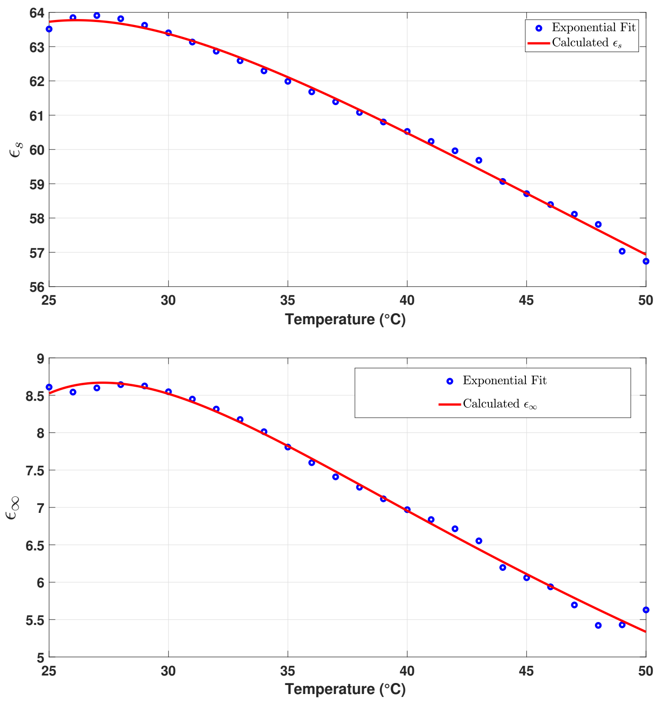


Figure 5.4 : ε_s, ε_∞ error rates of temperature-dependent three pole Cole-Cole parameters of real blood and blood phantom.

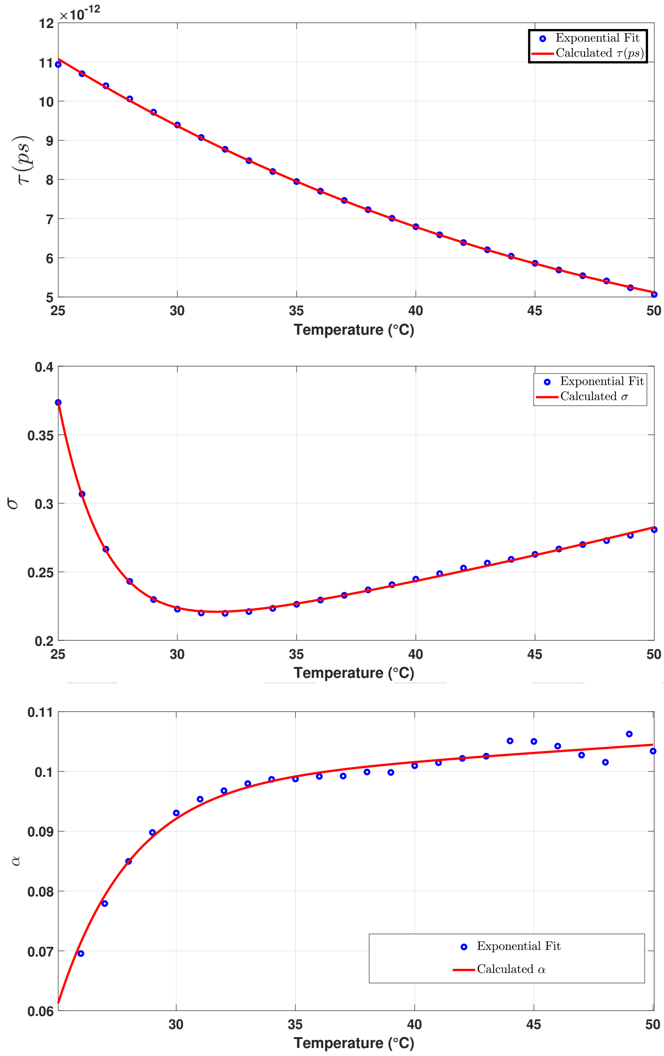


Figure 5.5 : τ, σ, α error rates of temperature-dependent three pole Cole-Cole parameters of real blood and blood phantom

of relative dielectric loss, this behavior is exactly the reverse. The calculation of temperature-dependent Cole-Cole parameters comes next. Tables 5.1, 5.2, and 5.3 provide the coefficients for the third-order polynomials in the three-pole Cole-Cole equation.

Next, we calculated the temperature-dependent Cole-Cole parameter coefficients, which are shown in Table 5.3. In order to confirm the accuracy of the fitting procedure, we lastly assessed the discrepancy between the fitted and measured data, as shown in Figure 5.7-8-9-10-11-12. The differences between the observed and fitted data are smaller than those found for dielectric loss and relative permittivity. Although we

Table 5.2 : Temperature coefficients of third order polynomial fit to the temperature-dependent three-pole Cole-Cole parameters of blood mimicking phantom

Parameters	A (K^{-3})	B(K^{-2})	C(K^{-1})	D	Adjusted R-Square Error
ε_∞	-0.0027	0.2642	-8.03103	77.970	0.939
ε_{s_1}	0.3082 $\cdot 10^{-3}$	-0.0396	1.3942	44.867	0.991
τ_1	-0.2386 (fs)	23.836 (fs)	-0.8764 (ps)	18.928ps	0.984
α_1	7.5138$\cdot 10^{-6}$	-0.7961$\cdot 10^{-3}$	0.0257	-0.2317	0.972
ε_{s_2}	0.0173	-1.3035	25.348	1349.2	0.662
τ_2	0.8111(ps)	-2.1585(ns)	0.1519 (μs)	0.445381μs	0.674
α_2	-9.8622 $\cdot 10^{-6}$	0.0010	-0.0376	0.9002	0.870
σ	-6.7682(muS)	0.9276(mS)	-0.0353(S)	0.4112	0.993

Table 5.3 : Temperature coefficients of third order polynomial fit to the temperature dependent three-pole Cole-Cole parameters of lung mimicking phantom

Parameters	A (K^{-3})	B(K^{-2})	C(K^{-1})	D	Adjusted R-Square Error
ε_∞	-3,1148$\cdot 10^{-5}$	0,0038	-0,1513	2,0062	0,234
ε_{s_1}	-0,1395 $\cdot 10^{-3}$	0,0108	-0,5147	62,383	0,997
τ_1	-70,607(as)	9,4836(fs)	-0,5503(ps)	18,163(ps)	0,996
α_1	1,9339$\cdot 10^{-7}$	-7,0018 $\cdot 10^{-5}$	0,0042	0,1469	0,860
ε_{s_2}	0,0398	-5,7831	234,88	-691,82	0,998
τ_2	34,8149(ps)	-2,5342(ns)	63,187(ns)	1,8746(ns)	0,999
α_2	-3,6530$\cdot 10^{-7}$	0,14065 $\cdot 10^{-3}$	0,12507 $\cdot 10^{-3}$	0,0830	0,999
σ	1,720(μS)	-73,089(μS)	-0,0031(S)	0,1416	0,967

were unable to obtain a reasonable fit for ε_∞ this time, the error is insignificant because the parameter's values are consistently less than 0.02 at all temperatures.

A great τ value indicates a bigger dielectric property change concerning frequency, whereas a small τ value indicates a limited variation in frequency. ε_∞ and $\delta\varepsilon$ are relaxation values that change the slope of the dielectric property curves. ε_∞ represents the relative permittivity at very high frequencies and $\delta\varepsilon$ symbolizes the deviation between static relative permittivity ε_s and relative permittivity at very high frequencies ε_∞. The symbol for ionic conductivity is σ_i Called Cole-Cole parameters, these are usually fitted to measurements of the dielectric properties to represent wide-band data with a small number of parameters.

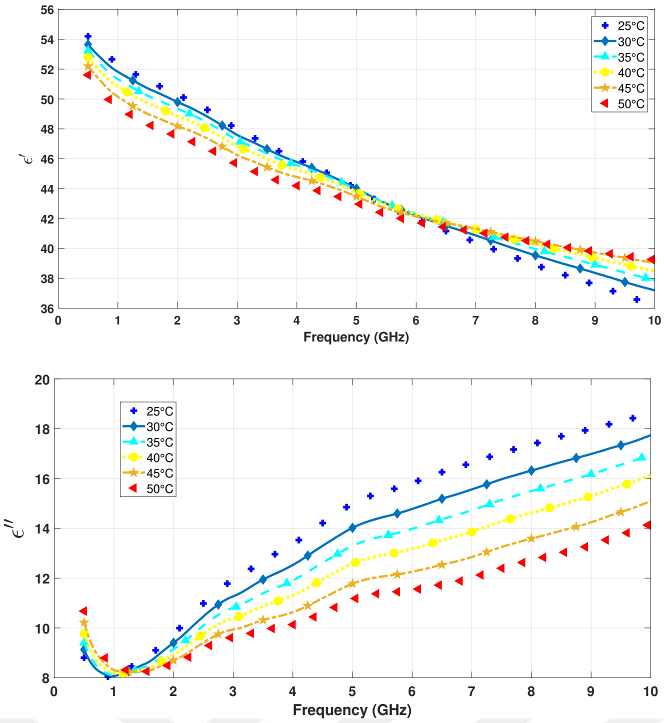


Figure 5.6 : Mean of measured (a) relative permittivity and (b) dielectric loss of lung mimicking phantom as a function of frequency at different temperatures, gathered during heating-cooling cycles.

The dielectric characteristics of the lung vary when the air content of this tissue changes. Throughout this study, we successfully reproduced the dielectric characteristics of a collapsed lung. Figure 5.6 displays the average values of the measured relative permittivity and dielectric loss at various temperatures of a phantom that mimics the properties of the lung. By observing the image, it is evident that the temperature profile aligns with that of other phantoms, and this characteristic corresponds to the data found in the literature.

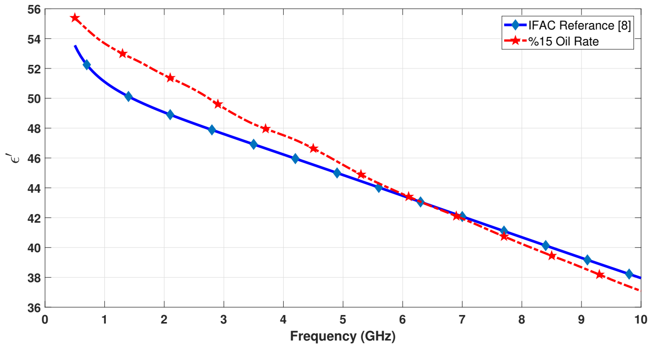


Figure 5.7 : Comparing the epsilon prime values of real lung tissue and %15 oil lung phantom from the IFAC website.

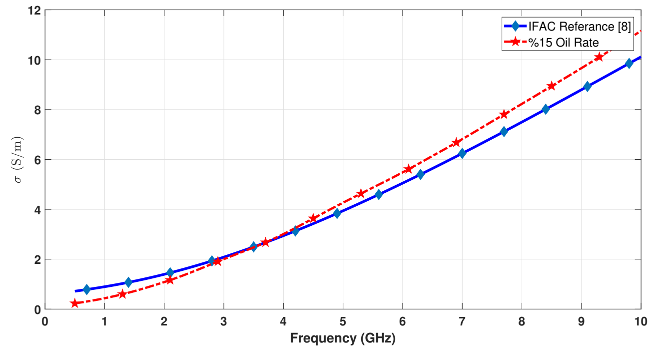


Figure 5.8 : Comparing the conductivity of real lung tissue and %15 oil lung phantom from the IFAC website.

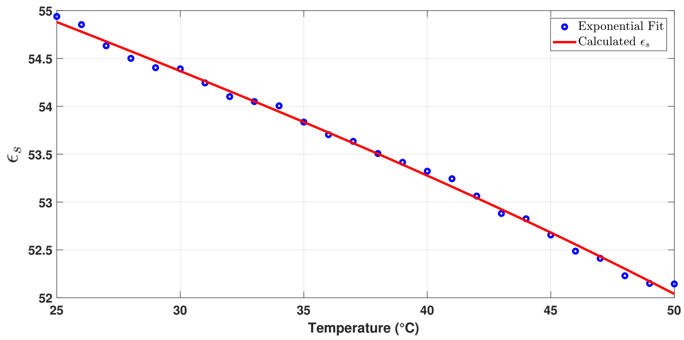


Figure 5.9 : ε_s error rates of temperature-dependent three pole Cole-Cole parameters of real lung tissue and lung phantom

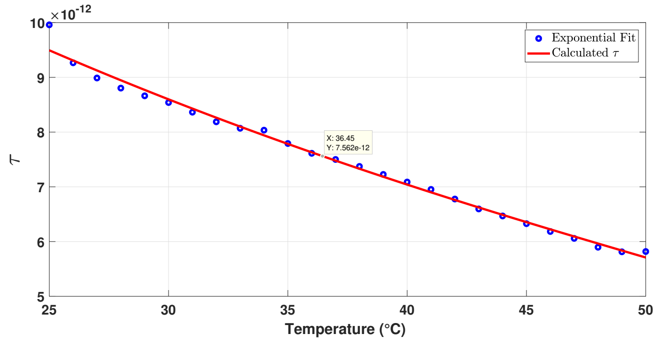


Figure 5.10 : τ error rates of temperature-dependent three pole Cole-Cole parameters of real lung tissue and lung phantom

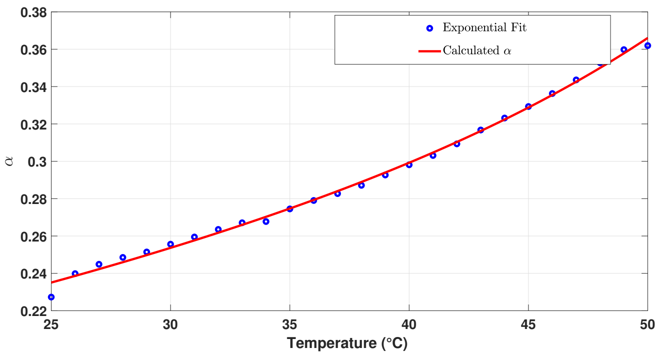


Figure 5.11 : α error rates of temperature-dependent three pole Cole-Cole parameters of real lung tissue and lung phantom.

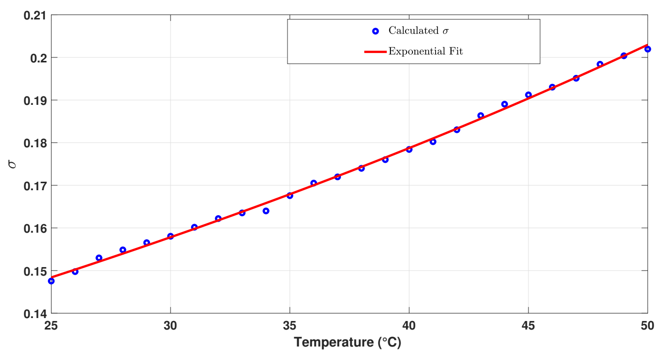


Figure 5.12 : σ error rates of temperature-dependent three pole Cole-Cole parameters of real lung tissue and lung phantom

6. CONCLUSIONS

As electromagnetic wave-emitting devices began to be utilized for diagnosis and treatment in medicine, the primary objective of this study was to investigate the temperature increase in tissue caused by microwave energy, particularly in the electrical dimension. There exists a direct correlation between dielectric properties and electromagnetic energy, as the absorption of this energy induces heating in the tissue. Understanding the changes in dielectric properties following this temperature increase in the tissues and comprehending the distribution of temperatures within the tissue will enable us to anticipate potential tissue damage. Another reason for conducting this study was to comprehend the electrical alterations in tissue subsequent to the thermal changes induced by treatments like ablation, as well as the early-stage diagnostic methods and clinical applications employing electromagnetic waves. Hence, twelve phantoms with tissue-like characteristics were fabricated for this study, with gelatin utilized as the primary material for all phantoms.

The oil-in-gelatin phantoms were prepared in a laboratory setting using gelatin, sunflower oil, dishwashing detergent, distilled water, and formaldehyde. A 3.5 mm open-ended coaxial. probe was employed for all measurements. Experiments were conducted within the range of 500 MHz to 10 GHz. To attain more precise results, three measurements were taken from distinct locations on each phantom, and the dielectric properties were determined by computing the average of all these measurements. During the calculation of the dielectric properties, assistance was sought from a code, and Cole. Cole parameters were utilized throughout the calculation process.

The measured dielectric values of the phantoms, both epsilon and epsilon prime, were compared with the data obtained from IFAC. It was observed that three phantoms containing 5 percent, 15 percent, and 35 percent oil exhibited similar characteristics to the electrical properties of blood, lung, and liver tissues, respectively. Moreover, the error rate remained below twenty percent. These three phantoms were once more employed to ascertain temperature-dependent properties. The phantoms were heated to 50 Celsius using a water bath and subsequently measured with an open-ended coaxial probe within the frequency band of 500 MHz to 10 GHz.

To calculate the temperature-dependent dielectric properties, it was modeled by fitting second-order polynomials to Cole-Cole parameters.

With fewer parameters, the second method enables the quantification of temperature dependency over a wide frequency range. However, in this study, third-order polynomials were employed to minimize the disparity between measured and calculated data. Third-order polynomials proved effective in reducing the absolute percentage error by up to %15. They were utilized to quantify the temperature-dependent changes in Cole. Cole parameters, with the parameters fitted at one-degree Celsius intervals. Since earlier studies demonstrated that a four-pole Cole. Cole equation more accurately captures the dielectric characteristics of biological tissue up to 20 GHz, a three-pole Cole-Cole equation was adopted for this research. The dielectric properties calculated using third-order parameters were compared with the electrical properties of real tissues documented in the literature, and error rates were calculated.

Based on all the results obtained, oil-in-gelatin phantoms have proven to be successful phantom types for tissue imitation. The dielectric properties measured at room temperature enabled us to achieve similar properties in various tissues. Furthermore, when evaluating the temperature-dependent dielectric properties in the second study, it has been observed that both the open-ended coaxial probe method and the utilization of the third-order Cole-Cole equation to determine heat-dependent properties yield results that are consistent with the literature. These results suggest a high potential for future studies.

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