A

Dissertation Report

on

A Generic Technique to Develop Human Tissue Phantom

Submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Technology
in
Electronics and Communication Engineering
by

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under the guidance of
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Certificate

This is to certify that the thesis titled "A Technique to Develop Human Tissue Phantom" submitted by Mir Mohsina (MT12096) for the partial fulfillment of the requirements for the degree of Master of Technology in Electronics and Communication Engineering is a record of the bonafide work carried out by her under my guidance and supervision in the Electronics and Communication group at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted anywhere else for the reward of any other degree.

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Abstract

Recent trends show increasing cases of implantable devices for monitoring and control of organs such as heart. The implantation of devices requires a multi stage evaluation process in order to make sure that these devices do not pose any harmful effects on the patients as well as to the surroundings. One important stage is the evaluation of implants in medium, called phantoms, resembling human organs. The phantoms can be heterogeneous or homogeneous mixture of different materials. Conventionally, the general procedure in developing such mixtures is to physically mix different materials in some arbitrary ratio, measure the electrical properties, such as dielectric constant, of the resultant mixture using Vector Network Analyzer and compare it with that of the actual human tissue involved in the application, discard it if the electrical properties do not match and repeat the process. This is obviously not a scientific approach and is highly cumbersome. In this thesis, we have proposed a three step procedure that is fast and accurate to develop human tissue phantoms based on FDTD method. At first, a software model is developed that mimics human tissue involved in the application and then a mixing approach is adopted that identifies the type and ratio of the materials to be mixed a priori. The results obtained from software model and the mixing technique compares favorably. As a last step, once the information about materials and their ratios are known, the components can be physically mixed to get the physical model of the human tissue.

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In the name of Allah, the Most Gracious and the Most Merciful

Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this thesis.

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Contents

List of Figures

List of Tables

1 Introduction

1.1 Introduction and Motivation

Medical implantable devices support and improve the quality of lives, playing a vital role in modern healthcare. The possibilities of communicating with the implantable devices open up many interesting outcomes. The main motive in such communications is to gather necessary information from the implants and to be able to program it remotely. This approach reduces the surgical operations that need to be performed on any human body in order to obtain the requisite biological data. For example, a pacemaker is used to make the heart beat in an orderly fash-

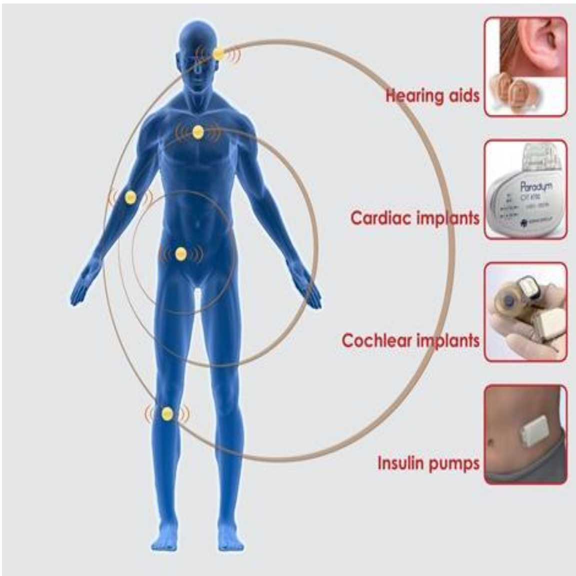


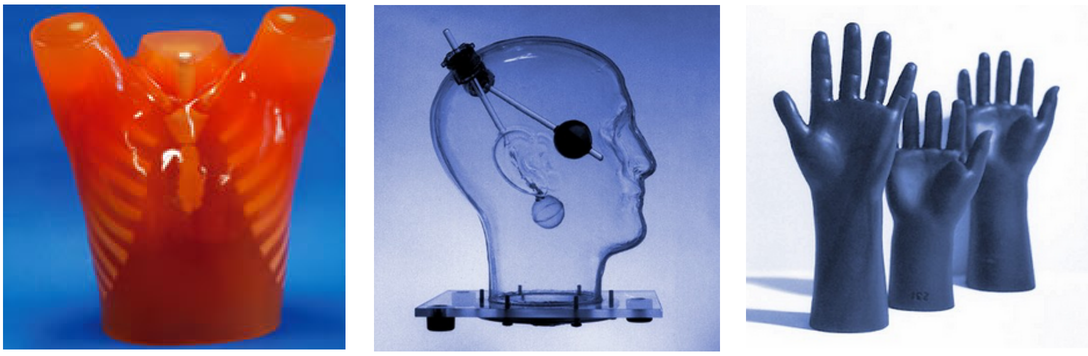
Figure 1.1: Wireless communication with medical implants *(http://www.tgdaily.com)*

ion. It is programmed such that whenever the heart rate falls below a fixed value, the pacemaker takes control of the heart and must be re-programmed to match with the heart's changing condition. Moreover, diagnostic information needs to be collected from the pacemaker. This communication can be achieved using an inductive link between a coil embedded inside the pacemaker and a coil placed upon the patient's chest, right on the top of pacemaker. However, this method provides a limited bandwidth and is too inconvenient for the patient. Therefore, a wireless communication link between the implanted device and the external environment is a preferred choice. This is achieved by fitting the pacemaker with a miniature radio transceiver. The antenna should be small and efficient enough to be unobtrusive in the body yet to carry radio signals across the body tissue. Also, designing antennas for embedded applications is extremely challenging because of power loss in tissues, size constraints, effect of surroundings on antenna efficiency etc [1].This requires a good estimation of the impedance variations of the implanted antenna. This necessitates the proper testing of antenna before surgical implantation in the patient's chest. It is important to note that the test and evaluation of these antennas should be carried out in an environment that closely resembles with the human body. Such an environment can be replicated using software or can be realized in physical form. The idea is to achieve electrical and biological properties that completely mimic the human chest. Such an environment is also necessary to study the effect of electromagnetic radiations from EM sources like mobile phones, ovens, industrial microwave instruments etc, on the human body by examining and analysing Surface Absorption Rate (SAR) of the human tissue. This model is given by “Phantom”.

1.2 Phantom

A phantom can be defined as a simulated biological body or as a physical model simulating the characteristics of biological tissues aiming to explore the interaction between human tissues and electromagnetic fields [2]. Phantoms have extensively been used in medical research to study the effects of electromagnetic radiations on human health as well as in the development various methods of medical diagnostic and treatment like X-ray, MRI Scan etc. For the communication devices like mobile phones which have to be operated very close to human tissue, phantoms become an essential tool for testing safety of these devices. Various safety guidelines regarding this are set up that specify the acceptable levels of radiation in terms of Specific Absorption Ratio (SAR) that can be measured using several methods involving phantoms. Phantoms also play a vital role in the study of radio wave propagation around and inside the human body to design powerful and robust wearable communication devices with relatively low cost. The use of phantoms provides a stable and controllable propagation environment that cannot be realized easily with live human subjects.

The phantoms can be categorized into numerical and physical phantoms. Numerical Phantoms can be divided into theoretical and voxel phantoms. Theoretical phantoms are simple shaped, homogeneous or layered flat phantoms that are generally used to evaluate EM dosimetry. Voxel phantoms, composed of many voxels (volume pixel), are more realistic form of numerical phantoms and are used to



(a) Chest Phantom **(b)** Liquid Head Phantom **(c)** Hand Phantom

Figure 1.2: Examples of Phantoms[*a:(https://www.kyotokagaku.com)b,c:(http://www.phantomlab.com)*]

calculate the characteristics of the antennas close to body. Physical phantoms can be classified based on the state of the phantom after the completion of the manufacturing process, which can be liquid, semi-liquid (gel) or solid (dry). Liquid phantoms are the first and oldest of all phantom types. It is a container filled with a liquid that has the same electrical characteristics as the tissues in the human body, in defined range of frequencies. For some applications the solidifying agent like agar, is used to make materials of jelly-like consistency that are capable of self shaping. A solid phantom is made of materials capable of keeping their shape and can best represent the inhomogeneous structure of the human body, but are difficult to fabricate compared to others. Figure 1.2 shows some examples of physical phantoms.

1.3 Dielectric Properties of Biological Tissues

When RF waves are directed towards a material, part of the energy is reflected, part is transmitted through the surface, and of this latter quantity, part of it is absorbed. The proportions of energy, which fall into these three categories, have been defined in terms of the dielectric properties.Thus, the dielectric properties of a biological tissue are a measure of interaction of elelctromagnetic radiation with its constituents at cellular and molecular level and are obtained from their measured complex permitivity. The real part of this complex quantity is the relative permitivity(ε_r) which gives the measure of energy stored in the material while its imaginary part gives the out of phase loss factor,a measure of electrical energy dissipated. When an EM signal is travelling from one tissue type to another, the impedance difference between the two tissue types results in the reflection of some energy reducing the power of the signal that travels to the other side of the interface. This gives the corresponding reflection and transmission coefficients which inturn can be used to calculate dielectric properties of the tissue.

The dielectric properties of biological tissues are highly frequency and temperature dependent. The effective permittivity $\varepsilon_r$and conductivity σ of different human tissues that are relevant for medical implants are given in Table 1.1. Biological tissues respond weakly to magnetic fields, so their permeability is approximated to unity. European Telecommunications Standards Institute (ETSI) has allocated a certain frequency band called Medical Implant Communication Service (MICS) band ranging from 402MHz to 405 MHz to all medical implantable devices. Also some of the implants may work in ISM (Industrial,Scientific and Medical) band. All data is given for a frequency of 403.5 MHz and 2.4 GHz and are from [3]. Notice that fat tissue is markedly different from both skin and muscle tissue in that it has a much lower permittivity and conductivity. We can also notice the frequency dependent nature of the tissue dielectric properties.

Table 1.1: Dielectric Properties of Human Tissues in MICS and ISM Bands

Tissue	Thickness(mm)	ε_r		$\sigma(s/m)$	
		403.5 MHz	2.4 GHz	403.5MHz	2.4GHz
Muscle	20	57.11	52.79	0.8	1.705
Fat	10	5.58	5.28	0.04	0.102
Skin	3	46.74	38.06	0.69	1.44

1.4 Objective

As will be discussed in chapter 2, various phantoms have been developed for different applications and the research is still going on. In the development of a complete phantom, as a first step, a software model is developed that accurately mimics the human tissue while the second step entails development of a physical model of the phantom, that has robust physical, biological and electrical properties. The physical phantom can be a heterogeneous or homogeneous mixture of different materials. The general trend in developing such mixtures is to physically mix different materials in some arbitrary ratio, measure the dielectric properties of the resultant mixture using Vector Network Analyser and compare it with that of the actual human tissue involved in the application, destroy it if there is an error and repeat the above process until the electrical properties of the mixture and human tissue match. This is a tedious and a non scientific approach. The basic motivation of this thesis is to put forward a technique by which the type and ratio of the materials to be mixed can be known beforehand. Once this information is known, the components can be physically mixed to get the physical model of the human tissue.

In this thesis, the human tissue modelled is the human chest which is envisaged to be used for pacemaker applications like pacemaker antenna testing and SAR measurements. The pacemaker is most often placed subcutaneously between the fat and pectoral muscles under the collar bone, so the human chest in this application can be well approximated by a three layer planar model consisting of muscle, fat and skin. The analysis is done using Finite Difference Time Domain method (FDTD). In this paper, all the research in the development of the phantom is limited within MICS band.

1.5 Organisation of Thesis

The rest of the thesis report is structured as follows:

- Chapter 2. Literature survey: Reviews the work already done in this field.

- Chapter 3. Proposed Methodology: In this chapter, the procedure followed and the details of the techniques used for the implementation is presented.

- Chapter 4. Implementation details and Results: This chapter describes the FDTD modelling of human chest and the mixture along with the results.

- Chapter 5. Conclusions and future work: This chapter highlights the conclusions of the proposed work and suggestions about the future work.

2 Literature Survey

Extensive research has been done in the development of the phantoms for various applications.In this chapter we present a thorough details spotlighting on previous key contributions to this area of research.

The knowledge of dielectric properties of human tissues is essential in the development of any type of phantom. Gabriel et.al, in 1996 [4][5][6][7], extensively studied and presented the dielectric properties of most of the human tissues as a function of frequency. Ibrani [8] in 2011, has formulated permitivity and conductivity equations of the biological tissues of children as a function of their height and weight. For developing a mixture,it is also necessary to know the dielectric properties of other materials existing in nature,with respect to frequency. There has been a lot of research in this area as well as in [9][10][11][12] etc.

Hartsgrove in 1987[13], has come up with the recipes for various human tissues like muscle, brain, lung and bones.The developed materials are easy to prepare, inexpensive, reproducible, and retain their properties for a long period of time. The dielectric properties were measured using an open ended co-axial line sensor and a computer controlled automatic network analyzer.

Karacolak in 2008 [14], developed skin mimicking gels to test MICS and ISM band implantable antennas for glucose monitoring applications. He has used Agilent's 85070E dielectric probe kit and HP8753D Network Analyser for developing the said phantom.Figure 2.1 is taken from the referenced paper. The proposed skin

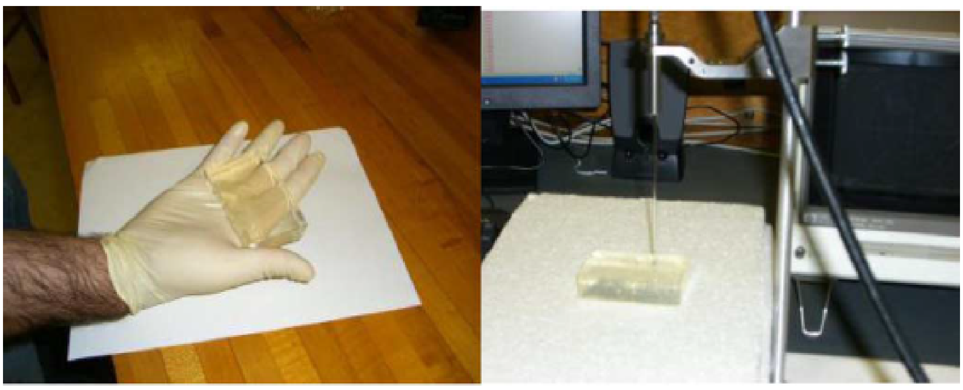


Figure 2.1: a)Skin mimicking gel (b)Measurement setup [14]

mimicking gel is composed of sugar and salt solution.Agarose has been used as gelling agent. The phantom developed at MICS band cannot be used in ISM band because of highly frequency dependent nature of tissue dielectric properties, so two different recipes have been proposed. Karacolak in 2009[15], also developed a rat skin mimicking gel to design and test implantable antennas for medical reseacrh in animals. Figure 2.2 shows the experimental setup for the same showing Agilent's dielectric probe kit and network analyser.

Figure 2.2: Experimental setup for developing rat skin phantom[15]

Until 1980's, liquid/semi liquid human tissue phantoms were used extensively because they were easy to use and didn't pose any problem during measurements. But reproducibility of such phantoms were a problem because their electromagnetic properties change with time due to bacteria invasion and dehydration.In 1990's, solid phantoms made of ceramics were developed but they had the problem of air gap between probe and hole at measurement interface. Choi in 2001[16], proposed a human body phantom which overcomes the limitations of both liquid and solid phantoms. The composition of the phantom is a shape memory polymer as base material and a dielectric material and a conductive material as fillers.

Kao in 2008 [17], developed an Electrical Impedance Tomography (EIT) phantom for medical imaging studies. The materials used to make this phantom show stable and usable electrical properties at EIT frequency (few KHz to 1 MHz) and are measured using Bioimpedance Analyzer and EIT system. He used banana, winter squash, cucumber and agarose as the sample materials to develop the desired phantom and after measurements found that agarose along with graphite powder yielded the best results.

There has been a lot of research in Ultrasound phantoms as well. Such phantoms should mimick the human tissue in at least three characteristics namely speed of sound, ultrasonic attenuation, and ultrasonic scattering. Madson et al. in 2002 [18], developed a tissue mimicking material for ultrsound phantoms made of aqueous mixture of large organic water soluble molecules condensed from skimmed milk with a total solids content in the range of 10% to 30% by weight. Similarly, Maggi in 2009[19], has developed ultrasound phantom that mimicks the acoustic properties of human soft tissues. The recipe he has come up with is silicone rubber

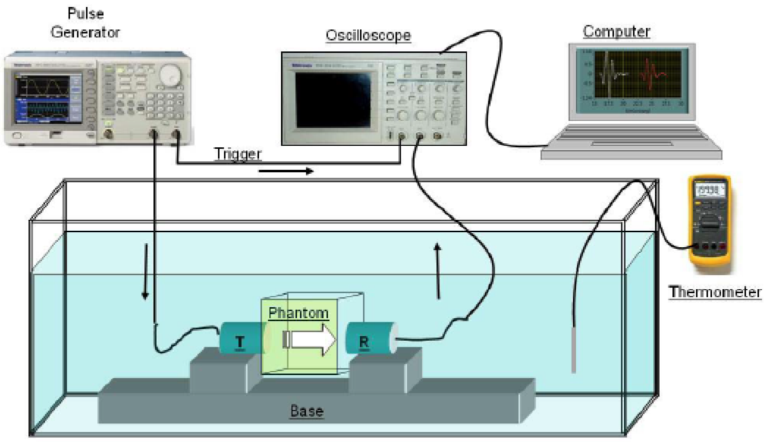


Figure 2.3: Experimental setup to develop ultrasound phantom(figure from [19])

mixed with silicone oil or glycerine or vaseline.The experimental setup for the same is shown in figure2.3. The silicone rubber was used as the basic medium and other materials with different concentrations were mixed to reach the values of acoustic properties within the range of biological tissues.

Ruvio in 2011[20], has developed a breast tissue numerical phantom to evaluate a detection algorithm for breast cancer diagnostics. The model used is a cylindrical structure which simulates skin and breast tissue layers. The tumour is modeled as a smaller cylinder located at an offset with respect to the origin of the breast phantom.Similarly, Andy and Ali in 2011[21], have developed a computaional breast phantom to measure the Mean Glandular Dose (MGD), a quantity to indicate the radiation risk in x-ray breast imaging technique. Bhatti in 2012 [22], developed a 3D software breast phantom using mechanical design tools to investigate the structure and function of soft tissues through elastography using Finite Element Method.

Various head phantoms have been developed for testing EEG equipment and noise rejection algorithms[23]-[26]. These phantoms have been successful in a number of ways, but they are not accurate in terms of electrical and mechanical properties. Moreover the materials used for making these head phantoms are not stable and lack repeated development. Colier et al in 2012 [27], developed a head phantom from solid and inherently stable materials for performance evaluation of EEG caps and associated technology. They used urethane resin and silicone with carbon dopings for brain and scalp respectively. Figure 2.4 shows the developed phantom. Image is taken from the associated paper[27]. The developed phantom is

Figure 2.4: Complete Skull Phantom[27]

anatomically more accurate model of the human head and is capable of repeated manufacturability. E.Mah et al. in 2001 [28]developed a chest phantom consisting of copper and aluminum cutouts arranged to resemble the appearance of a chest with embedded test objects like heart, lung and subdiaphragm, to evaluate the resolution and contrast detectability of digital radiography systems.Girnary in 2007 [29] developed a brain phantom made of 0.6% agarose gel to test a polymer implant device used for treating brain tumour.

Johansson in 2004[30], has developed a layered phantom to investigate the wave propagation from implanted pacemaker antenna to outside and its dependence on patient's limbs and the size of the body.The developed phantom has been conceptualized as a model of four tissue layers namely skin, fat, muscle, and lungs. All of these layers were first simulated individually using one and two-dimensional Finite Difference Time Domain (FDTD) simulations and eventually stacked to form the physical phantom. The modelling of the mixture developed has been done using Maxwell-Garnett mixing rule which models the mixture as spherical inclusions of one material inside a second, homogenous, background material.The recipe of the resulting phantom mixture is water, salt and sugar. Pekonen et al. [31] have validated various mixing rules with FDTD and have concluded that the FDTD scheme is a very powerful tool for creating a numerical mixture and studying its dielectric properties. Karkainin in 2001 [32], has reported a technique that offers the ability to study average characteristics of a random dielectric mixture.

From the above discussion, we can infer that the phantom mixture usually is developed by measurment techniques (as shown in different figures). In this thesis, we aim to develop these mixtures at software level first so that the information about the type and ratio of the materials to be mixed can be known beforehand. This way we need not to repeat the physical measurements for getting a match of the human tissues.

3 Proposed Methodology

3.1 Introduction

As compared to the method of developing phantom mixtures through measurements using VNA, the proposed method has potential to ease the phantom development prosess on one hand while on the other it can definitely aid in expediting the development process itself. As discussed in chapter 1, in this thesis we aim to develop a human chest phantom for pacemaker applications. To develop a material mimicking human tissue, it is necessary to first know the properties which we want to copy, of the latter. It is a well-known fact that an antenna implanted inside the tissue radiates in a high permittivity high conductivity media. It is also important to mention here that the effect of material on antenna radiation depends on the dielectric constant or complex permittivity of the material. Therefore, for example, the developed chest phantom is used for testing pacemaker antenna; the model should be an electrical equivalent of the actual human chest. Similarly, SAR measurements require the matching of electrical properties of the human tissue involved, characterized by its dielectric constant (ε) and conductivity (σ), which inturn can be extracted from their reflection (S_{11})and transmssion coefficients (S_{21}).Thus, it is imperative to know the equivalent electrical parameters of the human chest which acts as a reference data. This corresponds to Theoretical Phantom of the human chest. Then we try to match this truth data with the mixture of the materials,which gives the physical phantom.

3.2 Procedure

The steps followed are:

1. Modelling the actual human chest and calculating its equivalent reflection and transmission coefficients using FDTD

2. Validation of above results using analytical model

3. Modelling of mixture and determination of its reflection and transmission coefficients using FDTD

4. Comparison of 1 and 3 for error minimization

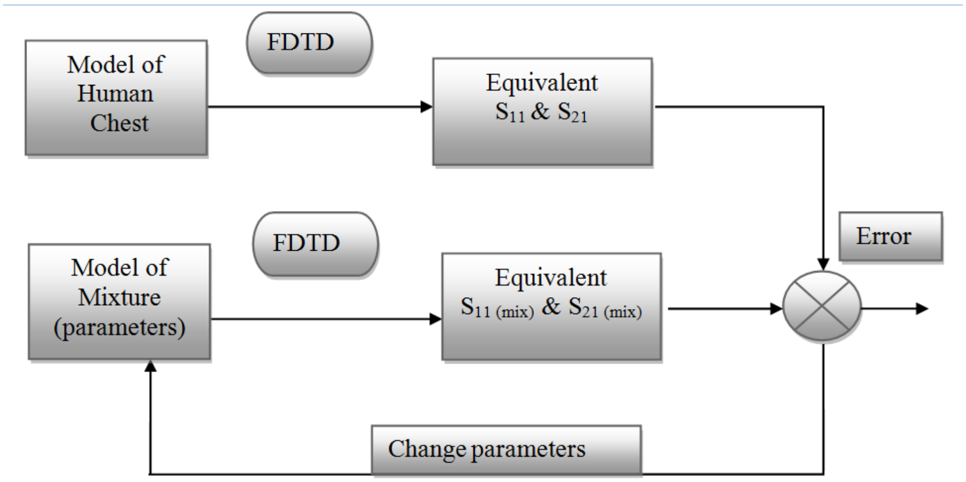


Figure 3.1: Flowchart

3.3 Employed Computational Technique

The computational electromagnetic technique used to determine the reflection and transmission coefficients of the human chest and the mixture is Finite Difference Time Domain (FDTD), which is a powerful method of solving Maxwell's equations in one, two or three dimensions and in time. It was proposed by Yee in 1966 and since its inception its popularity among various numerical methods for solving arbitrary electromagnetic problems has increased. The Maxwell's equations for dispersive materials can be written as:

$$\nabla \times \overrightarrow{H} = \sigma \overrightarrow{E} + \frac{\partial \overrightarrow{D}}{\partial t} \tag{3.1}$$

$$\nabla \times \overrightarrow{E} = -\frac{\partial \overrightarrow{B}}{\partial t} \tag{3.2}$$

Where, $\overrightarrow{E}$ is the electric field intensity, $\overrightarrow{H}$ is the magnetic field intensity,σ is the conductivity of the medium, $\overrightarrow{B}$ is the magnetic flux density, $\overrightarrow{D}$ is the electric flux density, respectively given by

$$\overrightarrow{B} = \mu_0 \overrightarrow{H} \tag{3.3}$$

$$\overrightarrow{D} = \varepsilon_0 \varepsilon_r \overrightarrow{E} \tag{3.4}$$

where μ_0 is the permeability of freespace, ε_0 is the permitivity of free space, ε_r is the relative permitivity of the medium. We consider TM mode with $\overrightarrow{E_x}$and $\overrightarrow{H_y}$components. The field components are updated in leapfrog scheme using finite difference form of the curl operators on the fields that surround the component. After solving, the final FDTD equations can be summarized as:

The Electric Flux Density, $\overrightarrow{D_x}$ is given by:

$$\overrightarrow{D_x}(n,k) = \overrightarrow{D_x}(n-1,k) + \frac{1}{2*c_0}[\overrightarrow{H_y}(n,k-1) - \overrightarrow{H_y}(n,k)] \tag{3.5}$$

$$\overrightarrow{H_y}(n+1,k) = \overrightarrow{H_y}(n,k) + \frac{Y_0}{2*\mu_r(n,k)}[\overrightarrow{E_x}(n,k) - \overrightarrow{E_x}(n,k+1)] \tag{3.6}$$

Wheren, k are the discrete units of time and space, respectively and $Y_0$is the admittance of freespace. The electric field, $\overrightarrow{E_x}$ is given by:

$$\overrightarrow{E_x}(n,k) = \frac{\overrightarrow{D_x}(n,k) - \overrightarrow{I_x}(n-1,k)}{\varepsilon_0\varepsilon_r(k) + \sigma(k)\triangle t} \tag{3.7}$$

Where ,$\triangle t$ is the unit time step and $\overrightarrow{I_x}(n,k) = \sigma * \triangle t * \sum \overrightarrow{E_x}(n,k)$[36].This time domain data is then converted into frequency domain using Fast Fourier Transform (FFT), in order to get the reflection and transmission coefficients.

The determination of reflection $|S_{11}|$ and transmission $|S_{21}|$ coefficients of a multilayer dielectric structure, can be done by various methods like TMM (Transfer Matrix Method), Method of Moments (MOM), Finite Element Method (FEM), FDTD, Transmission line analogy etc. But at MICS frequencies FDTD is an effective tool for analyzing wave propagation in confined spaces. The fidelity of the simulations with actual measurements is good [30]. Also modeling of mixture isn't possible with all these methods. Mixtures can be modeled using various mixing rules like Maxwell Garnett's formula, Bruggman's formula, Litchterecker's mixing rule etc. But, as discussed in chapter 2, Pekonen in his paper [31], has demonstrated that FDTD is a very powerful tool when studying the dielectric properties of mixtures. The mixing rules also have certain specific ranges of validity and cannot be applied to all materials under all conditions. Moreover as the number of constituents in the mixture increases, the complexity of these rules also increases. Also for applying mixing rules, it is essential to extract required equivalent permittivity from frequency dependent reflection and transmission coefficients. In this thesis, we have directly used S_{11} and S_{21} to calculate the ratio and type of the constituents of the mixture and FDTD proved to be very easy to use tool.

3.4 Analytical Model for Validation of FDTD Results

The FDTD results have been validated by using basic plane wave propagation formulae and the concept of transmission line analogy of wave propagation [34][35].

Consider a multiple interface problem with $N+1$ planar regions separated by N interfaces. The multilayer problem thus looks like figure 3.2.

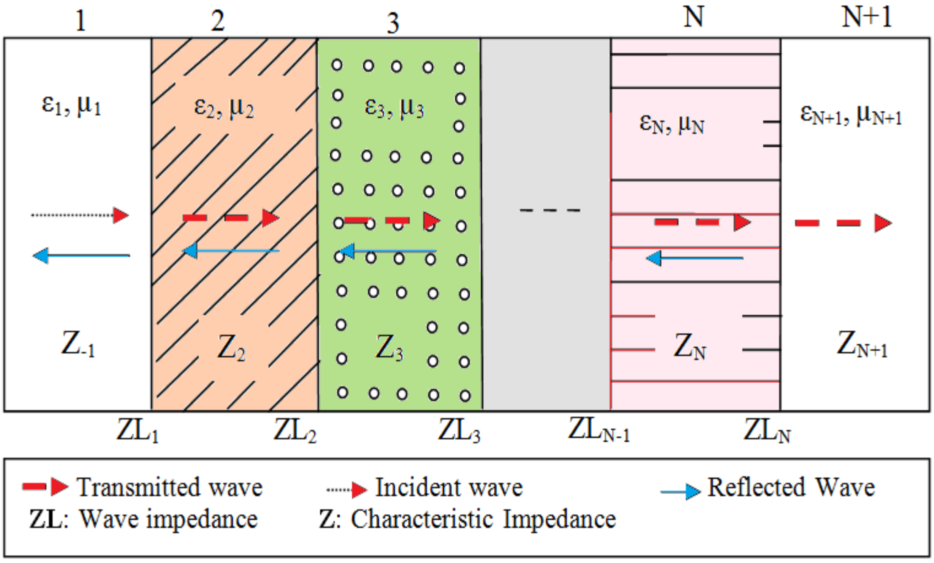


Figure 3.2: N-layered dielectric media

As seen in the figure, in each layer, there are both transmitted and reflected waves, except for the last layer where no reflection takes place. Therefore the wave impedance as seen fromNth interface is equal to the characteristic impedance of the $(N+1)$th layer i.e

$$ZL_N = Z_{N+1} \tag{3.8}$$

The recursive relation for calculating wave impedances at each interface is given by:

$$ZL_{n-1} = Z_n[\frac{1 + (R_n * exp(-2j\beta_n t_n)}{1 - (R_n * exp(-2j\beta_n t_n)}] \tag{3.9}$$

where $n = 2, 3, 4, ...N$, $'ZL'$ is the wave impedance at each interface,'Z' is the characteristic impedance of medium, β is the propagation constant of the medium, $'t$' is the thickness of layer and 'R' is the reflection coefficient given by

$$R_n = \frac{ZL_n - Z_n}{ZL_n + Z_n} \tag{3.10}$$

where $n = 1, 2...N$. R_1will give the equivalent reflection coefficient of the whole structure. Similarly, for transmission coefficient,T, the electric fields at each interface is calculated by the recursive relation:

$$E_n = E_{(n-1)} * [\frac{1 + R_{(n-1)}}{exp(j\beta_n t_n) + (R_n * exp(-j\beta_n t_n))}] \tag{3.11}$$

where, $n = 2, 3, ...N$. Therefore, the transmitted electric field and hence the equivalent transmission coefficient is given by:

$$E_{(N+1)} = E_N[1 + R_N] \tag{3.12}$$

$$T = \frac{E_{(N+1)}}{E_1} \tag{3.13}$$

where E_1 is the electric field strength in first layer. These formulations were coded in MATLAB and the results were used to validate FDTD results.

4 Implementation Details and Results

In this chapter, we discuss how the above proposed approach has been implemented and consequently getting the results fulfilling the objective of this thesis.

4.1 Modelling of Human Chest and Results

As discussed in chapter 1, in this thesis we are developing a chest phantom for pacemaker applications like SAR measurements or antenna testing. The human body is a heterogeneous media consisting of multiple layers of tissue with varying dielectric properties which are frequency dependent. A model representing the body for some application should account for all these layers. For reasonable analytical calculations, these layers can be simplified to rectangular slabs. The pacemaker is most often placed subcutaneously between the fat and pectoral muscles under the collar bone so the human chest in this application can be well approximated by a three layer planar model consisting of muscle, fat and skin as in figure 4.1.

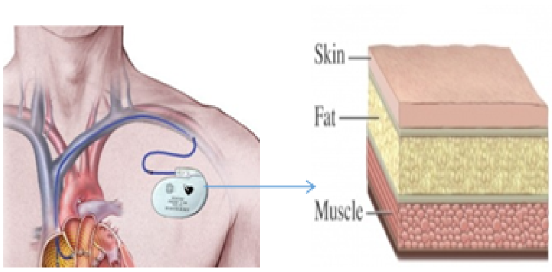


Figure 4.1: Different layers of human chest

The problem can be visualized as shown in figure 4.2.

The problem has been approached by designing a one dimensional FDTD simulation space of length 0.0396 m, made up of three different layers, representing the three layers of human chest tissue, i.e muscle, fat and skin. These layers are

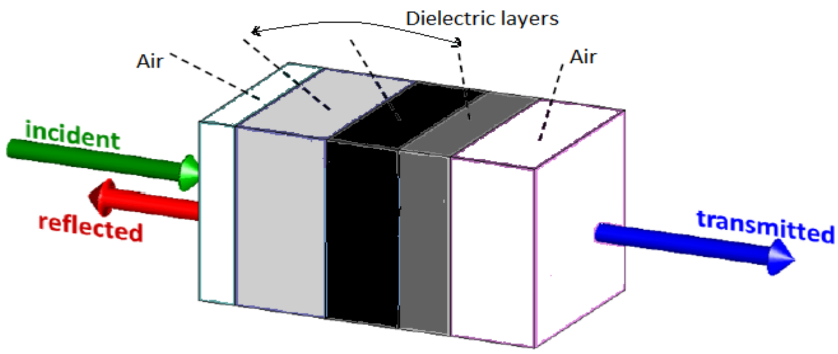


Figure 4.2: 3D view of the problem

surrounded by free space on both the sides wherein source and various ports to be examined are placed. Moreover, the thicknesses of various layers have been kept equal to their biological thicknesses for an average male adult. This is diagrammatically shown in Fig.4.3

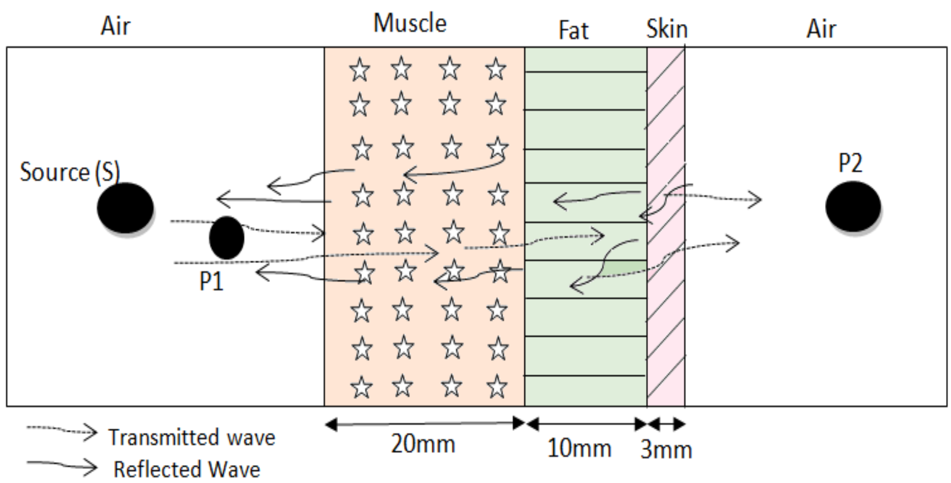


Figure 4.3: Problem space diagram of human chest

At port 'S', the source is present, followed by port 1, where equivalent reflection coefficient (S_{11}) is determined while at port 2, equivalent transmission coefficient (S_{21}) is calculated. A Gaussian pulse is used as the excitation source. The cell size is 0.33mm and the frequency resolution is 0.5MHz which is imperative for a very narrow frequency range of MICS band. One simulation is run as long as is needed to sufficiently dissipate the energy launched in to the computational space. The reflection and transmission coefficients are determined by calculating the frequency domain electric fields from time domain electric fields at specified positions in FDTD sample space as:

$$S_{11}(f) = \frac{E_{ref}(f)}{E_{inc}(f)} \tag{4.1}$$

$$S_{21}(f) = \frac{E_{trans}(f)}{E_{inc}(f)} \tag{4.2}$$

Where E_{total} is the total electric field calculated at port 1with the medium, E_{trans} is the transmitted electric field calculated at port 2, E_{inc} is the incident electric field calculated at port 1,without medium (i.e only free space) and E_{ref} is the reflected field given by $E_{total} - E_{inc}$.Figure 4.4 shows the magnitude of S_{11} and S_{21} in MICS band (402-405MHz) calculated as shown above and its comparison with the analytical results .

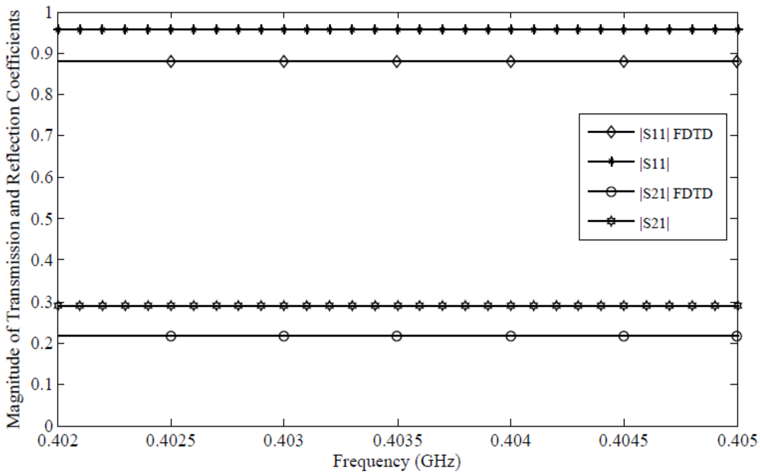


Figure 4.4: Equivalent Reflection and Transmission coefficients of human chest from FDTD and analytical method

From this figure we can infer that the magnitude of S_{11} and S_{21} doesn't show any significant variation in such a narrow frequency band (MICS). So, the equivalent $|S_{11}|$and $|S_{21}|$ for the human chest approximated to a three layer planar structure is 0.88 and 0.23 respectively. The analytical results show an $|S_{11}|$ of 0.95 and an $|S_{21}|$ of 0.29 as shown in table 4.1. Hence, the two results favourably agree with each other. The difference in results is due to the fact that the analytical model takes only far-fields into account while FDTD takes both near and far field into consideration. This validates our FDTD results. Moreover these results act as the reference data for further calculations.

Table 4.1: Results from FDTD and Analytical model of human chest

S-parameters	FDTD model	Analytical model
S_{11}	0.88	0.95
S_{21}	0.23	0.29

4.2 Modeling of Mixture and Results

The simulated structure for the mixture is shown in fig.4.5. The material mixture comprises of the host and inclusion materials in the form of the slab sandwiched between two air layers. The rest of the problem space is same as described above for modeling chest.

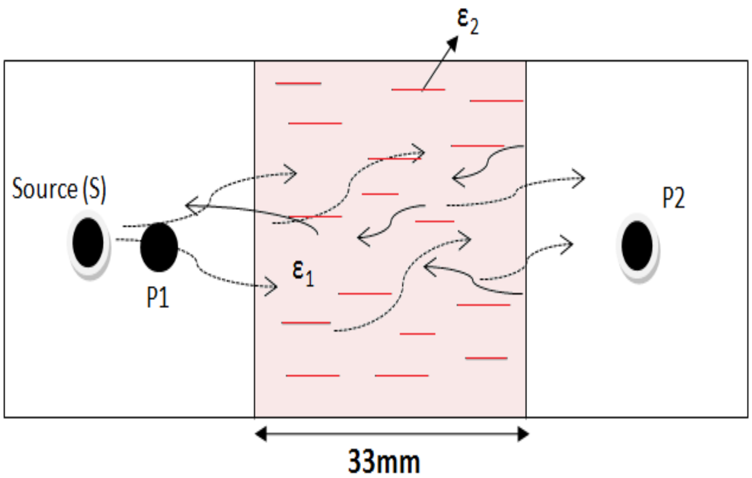


Figure 4.5: Problem space for mixture model

The calculation of S_{11} and S_{21} for this mixture is the same as discussed in above section. Different parameters involved in the mixture modeling are:

1. The number of materials with different dielectric constants to be mixed.
2. The percentage of one material into another.

These are the parameters which we need to change until we get the minimum error between the mixture S-parameters and the reference data. One of the parameters is kept fixed and the other is changed to get the desired results. This will ensure that the mixture developed approximately mimics the electrical properties of the human chest. It is a known fact that all the materials existing have greatly varying electrical properties i.e dielectric constant (ε) & conductivity(σ) at different frequencies. So it is necessary to know the properties of the constituent materials to be used for mixing, in MICS band. We have taken some sample materials for testing as given in the table 4.2. The values have been taken from [9][10][11][12].There are few assumptions to be taken care of while mixture modeling in this thesis.

Assumptions:

1. Materials chosen should not form a homogenous mixture.
2. The dielectric properties of all the materials taken, do not fall in MICS band but is in the range of 400-500 MHz.

Table 4.2: Sample materials taken

Material	ε_r	$\sigma(s/m)$
Dry Sand	2.7	0.0063
Basmati Rice	3.33	0.02527
Lentil Flour	6	0.11
Wheat Protein	28.5	7.93
Cheese	43	22.833
Milk	57.9	0.01
Whey Protein	75	12.9
Deionized Water	78.7	3.104

As seen in table 4.2, the dielectric constant of water,whey protein, wheat protein ,milk and cheese are comparable to the dielectric constants of muscle and skin. So these materials are mixed with sand,flour and rice with low permitivity to get the desired results. The combinations have been chosen keeping in view both the permitivity and conductivity values of the materials. We have considered low permitivity material as a base material while the others as inclusions. The reverse can also be done. Now, since the distribution of the inclusions are random, it is not sufficient to perform just one simulation for one percentage. So there is a need for monte carlo simulations. We have performed 50 simulations to validate the results with different inclusion location densities. We tried with different combinations of the above mentioned materials and got the results as shown in figure 4.6 and 4.7 .The results have also been given in table 4.3.

To Start with, we have kept the number of materials fixed to two and have changed the percentage of one in other.For each combination we have started with the pure material and then doped it with the other increasing the percentage of the latter in the former. As seen from the table, the root mean squared errors for $|S_{11}|$ and $|S_{21}|$ does not show the same trend.For each combination, if the RMSE of $|S_{11}|$ decreases, its RMSE of $|S_{21}|$ increases. For example, the least error in$|S_{11}|$ is 1% which can be acheived by mixing 20% wheat protein with rice but RMSE of $|S_{21}|$ for the same combination is 80%. Hence,the combination with acceptable errors in both the parameters need to be considered. From the above figures and corresponding table, we can infer that among the different combinations of sample

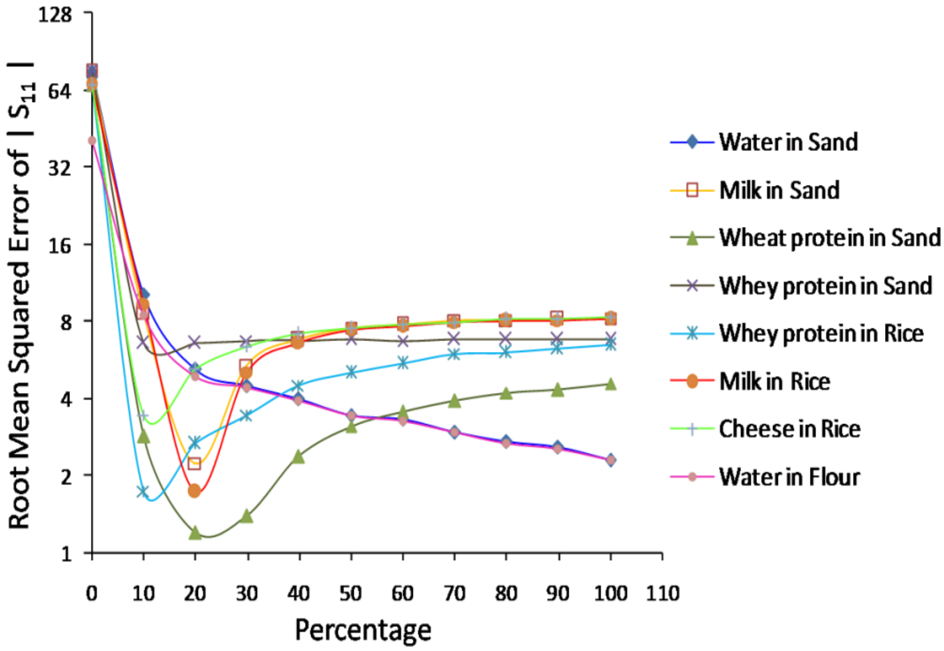


Figure 4.6: Root Mean Squared Error of $|S_{11}|$

materials,the combination of “10% water in sand” and “10% water in lentil flour”, gives the least error for both the paramters. We can also increase the number of materials to three and repeat the same process and try to minimize the error further. But with the sample of materials taken, addition of any third material will worsen the error. Now,the ratio of water and sand or water and flour to be mixed is known, we can mix them physically to get the physical phantom which was the goal of the thesis.

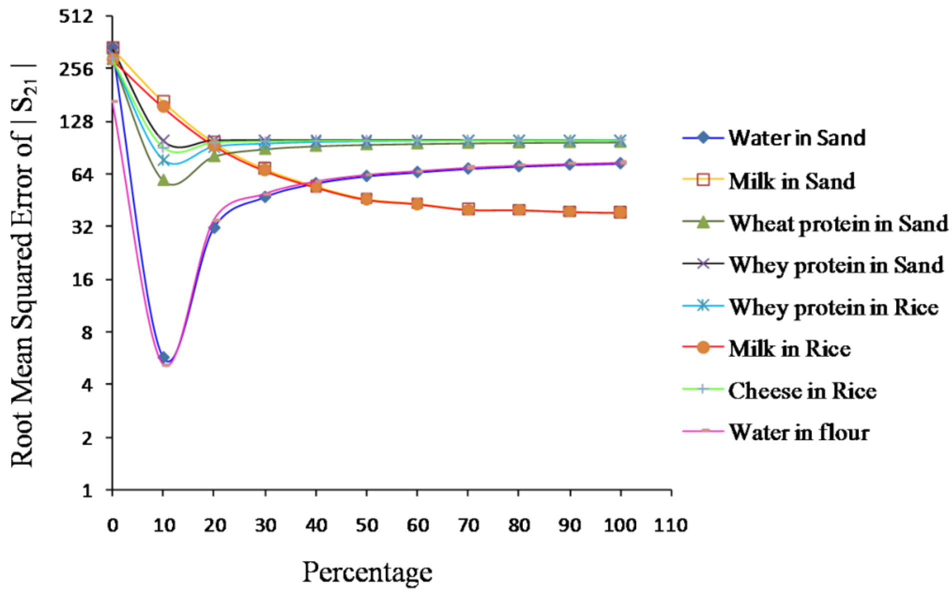


Figure 4.7: Root Mean Squared Error of $|S_{21}|$

Table 4.3: RMSE of Reflection and Transmission Cefficients

	Water in Sand		Water in flour		Milk in Sand		Wheat in Rice		Whey in Sand		Whey in Rice		Milk in Rice		Cheese in Rice	
Percentage	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$	$\|S_{11}\|$	$\|S_{21}\|$
0	75	334	41	163	75	334	67	287	75	334	67	287	67	287	67	287
10	**10**	**5.7**	**8.3**	**5.1**	8.5	165	2.8	58.5	6.59	98	1.7	76	9.3	152	3.4	91
20	5	31.4	5	34.6	2.2	96	1	80	6.56	98.8	2.6	90.6	1.7	92	5	97
30	4.4	47	4.4	49	5.4	68	1.3	88	6.72	99	3.4	94.3	5	66	6.3	98
40	4	56	4	57	6.7	54	2.3	91.6	6.74	99	4.4	96.3	6.5	53	7	99
50	3.4	62	3.4	62	7.5	45.7	3.1	93.4	6.8	99	5	97.2	7.3	45	7.4	99
60	3.3	65	3.2	66.7	7.7	43	3.5	94.4	6.7	99	5.4	97.8	7.6	42	7.7	99
70	3	68	3	68.7	8.07	39.7	4	95.3	6.8	99	5.9	98.2	7.9	39	7.9	99
80	2.6	70	2.6	70.7	8.09	39.6	4.2	95.8	6.8	99	6	98.4	7.9	39	8	99
90	2.5	72	2.5	72	8.17	38.5	4.3	96	6.8	99	6.2	98.6	8	38	8	99
100	2.3	73	2.2	73.4	8.21	38.1	4.5	96.5	6.8	99	6.4	99	8.1	38	8.3	99

5 Conclusion and Future Work

The technique to develop human tissue phantoms, for example, a chest phantom for pacemaker applications, has been developed successfully. The reflection and transmission coefficients of equivalent human chest have been determined and the required composition of the human chest phantom at MICS band has been achieved beforehand without any experimental measurements. This aim has been acheived by using FDTD method and the validation has been done using analytical approach. The combination of water in sand and water in lentil flour gives the least error possible with the sample materials and hence the highest match with the electrical properties of the actual human chest. This technique is generic and is applicable to other tissues at other frequency bands as well.

The future work includes:

1. The information about the mixture composition can be used to make the real physical phantom.

2. A pacemaker antenna can be tested in this phantom, in addition to the measurement of Surface Absorption Rate (SAR) of the radiaition from the antenna.

3. The same analysis can be done for ISM (Industrial, scientific and Medical) band.

4. The equivalent dielectric constant of the human chest tissue can be extracted from the determined equivalent transmission and reflection coefficients.

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