IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 4, 2021, accepted November 30, 2021, date of publication December 3, 2021,
date of current version December 13, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3132691

Development of a Theoretical Microwave Model to Predict the Dielectric Properties of Articular Cartilage Tissues

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ABSTRACT Recently, a growing research on the electromagnetic properties of biological tissues has been observed, particularly at microwave frequencies. The frequency variation of the dielectric properties of tissues at microwave frequencies may be described by the Cole-Cole relaxation model. This model is frequently used by researchers to extrapolate the measured permittivity data to higher frequencies based on polynomial frequency fits. Robust theoretical model that takes into consideration the geometry and distribution of tissue materials is much demanded. The aim of this paper is to develop a structured model to predict the dielectric properties of human cartilage tissues based on their microstructure. The presented approach is multi-scale which begins from the microscopic scale and derives the macroscopic properties after several scale-steps. The predicted model agrees reasonably with the estimated values of Cole-Cole relaxation model. Such a model would be useful in developing microwave imaging and patient treatment planning. Moreover, this model is expected to find application in non-invasive medical sensing where it can relate dielectric response to pathological structural changes in the tissue.

INDEX TERMS Cartilage tissues, relaxation models, theoretical modeling of electrical properties, tissue dielectric permittivity.

I. INTRODUCTION

Dielectric properties specifically, conductivity and relative permittivity, are inherent characteristics of biological tissues and determining factors for the transmission, reflection and absorption of electromagnetic energy in the human body. Absorption and penetration of electromagnetic waves are dependent on tissue composition and interfaces [1]–[3]. Knowledge of the dielectric properties of human tissues is needed in order to understand specific medical techniques and for some biophysical processes. Moreover, the dielectric properties of tissues are essential in a wide variety of applications, including dosimetry safety calculations and the design of diagnostic medical devices. Therefore, in order to understand the effect of electromagnetic waves on the human tissue, it is important to know accurately its complex dielectric permittivity as well as its conductivity [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Rajeeb Dey.

Currently; it has been only a limited number of studies of the dielectric properties of healthy human tissues at higher microwave frequencies. The lack of data is due to technical difficulties in using real human samples for experimental measurements. The preparations of the samples, handling and sorting these samples are also major issues. The most comprehensive survey to date was published in 1996 [5]–[7]. This study covers a large selection of healthy tissue over a wide spectrum of frequencies (100 MHz - 20 GHz). In cases where dielectric data of human tissues are needed in a different band it has become customary to predict the required values of permittivity and conductivity using standard relaxation models as the dielectric behavior of biological tissues can be described by a number of relaxation phenomena.

In biological tissues, both the dielectric permittivity and conductivity are strongly non-linear functions of frequency. The frequency dependence of the dielectric properties of biological tissues can be described mathematically using empirical equations known as relaxation models such as Debye

and Cole-Cole model [8]. These models are mainly based on polynomial fits to the measured data at different frequencies. Empirical models are commonly used by researchers that are based on polynomial frequency fits to measured permittivity data [9]. Unfortunately, measurements are very scarce over a wideband of frequency. This makes modeling process difficult; hence simplifications are always needed in the research area [10]. Tissue structure is complicated and highly variable. The variety of cell shapes and their distribution inside the tissue as well as the different properties of the extracellular media complicate a microscopic description of the response of a tissue to electric stimulation [11]. Therefore, a macroscopic approach is frequently used to characterize field distribution in biological tissues. The natural variability of the literature data of biological tissues along with the tolerance on experimental data permits several models to be accommodated [12]. In general, the combined knowledge of tissue composition and microstructure could be used to derive theoretical estimates of tissue dielectric properties. Theoretical models are a simpler representation of reality, which help to explain and predict the behavior of real complex systems. Comparative studies of different theoretical models relating the tissue microstructure to its dielectric permittivity are presented in literature. For example, a theoretical model of the skin tissue is reported in the RF frequency range [13]. Also, a theoretical model of the cornea tissue is reported in the 0.4 - 10 GHz frequency range [14].

Articular cartilage is a fibrous connective tissue which functions as a structural support while remaining flexible. It is made up of specialized cartilage cells that produce a matrix of collagen, proteoglycans (a special type of protein) and other non-collagenous proteins. These materials help cartilage to attract water and give it its shape and specific properties. Literature data indicated that the dielectric permittivity of cartilage has been found to increase with decreasing frequency. The first study to examine the electrical conductivity of the cartilage tissue was done by Maroudas, using a two-electrode method on human cartilage. It was realized that the tissue conductivity is controlled by the geometry and characteristics of the tissue, as well as the electrode configuration [15].

In this paper, we introduce, for the first time, a theoretical structured model to predict the electrical properties of the cartilage tissue based on its physical composition. The dielectric model is developed across a wide frequency range of 100 MHz to 20 GHz. To validate our model, the permittivity as well as the conductivity for cartilage tissues is then compared with known reference data from literature. The results of the current study suggest that treating the cartilage tissue as homogeneous organ may not accurately represent the actual properties. Its heterogeneity should be considered in order to achieve a fully accurate dielectric profile. The proposed dielectric mixture model can be used to estimate the dielectric properties of cartilage tissues in order to improve the accuracy and reliability of electromagnetic-based medical treatments.

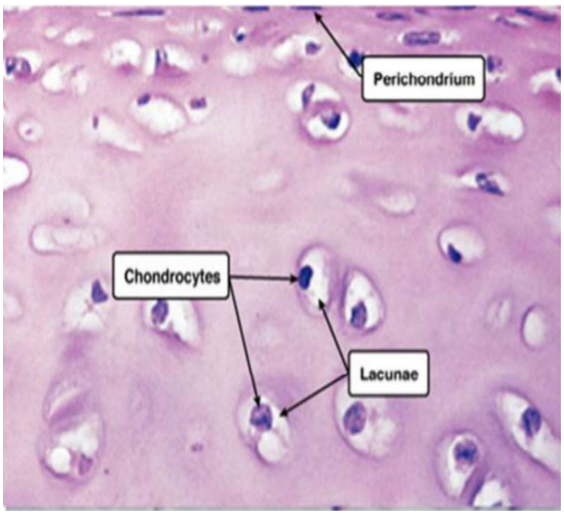
II. CARTILAGE TISSUE HISTOLOGY

Cartilage is a specialized fibrous connective tissue which functions as a structural support while remaining flexible. It is consisting of cells called cartilaginous cells and a basic substance containing short and dispersed collagen fibers. Cartilage tissue can be found in different parts of the human body such as joints between bones (e.g. the elbows, knees and ankles), the rib cage, the nose, and the ear. It also forms most of the skeleton of an embryo. Its structure has special functions such as shock absorbing or achieving the movement of the joints of the body without friction [16].

Cartilage tissues are classified into three types: hyaline cartilage, white fibrocartilage, and elastic cartilage. Hyaline cartilage has a smooth surface and is the most common of these three types. Because of its smooth surfaces it allows tissues to slide more easily, as well as providing flexibility and support. It has an extracellular matrix (ECM) that contains closely packed collagen fibers, making it tough but slightly flexible. As a consequence of various functional requirements, the three different forms of cartilage have evolved each exhibiting variation in matrix composition. Hyaline cartilage is easily distinguished from elastic and fibrocartilage because of the homogeneous extracellular matrix [17]. Articular cartilage (AC) is a hyaline cartilage that lies on the surface of bones and it is about 2 to 4 mm thick [18].

Articular cartilage is composed of specialized cells called chondrocytes. These cells are located close to the edge. The chondrocytes produce an extracellular matrix composed of collagen fibers, proteoglycan (PG), and elastin fibers. The chondrocytes are spherical in shape and isolated in small lacunae within the matrix [19]. Some lacunae contain only one cell; others contain two, four, or sometimes six cells. These multicellular lacunae are called cell nests or isogenous groups. The differentiated chondrocytes comprise less than 10% of the matrix by volume and/or weight [20]. The extracellular matrix shields the ensconced chondrocytes from the high stresses and strains generated by joint loading. Articular cartilage does not contain vessels and receives nutrients via diffusion by a cartilaginous membrane called the perichondrium. The perichondrium is a connective tissue sheath covering that overlies most cartilage. The perichondrium is vascular, and its vessels supply nutrients to the cells of cartilage. Perichondria are present in elastic and most hyaline cartilages, but absent in fibrocartilage.

The histology of the hyaline cartilage tissue is shown in Figure 1. It is seen that the tissue is composed of dense extracellular matrix with a sparse distribution of tightly packed specialized cells called chondrocytes. The matrix is mainly composed of water, collagen, and proteoglycans, with other non-collagenous proteins and glycoproteins present in lesser amounts. The ground substance is an amorphous gel-like material composed of polysaccharide chains (glycosaminoglycans (GAG)) bound to protein [21]. The outer



Cartilage is a connective tissue consisting of chondrocytes that produce a large amount of collagenous extracellular matrix within a water-rich, gel-like ground substance.

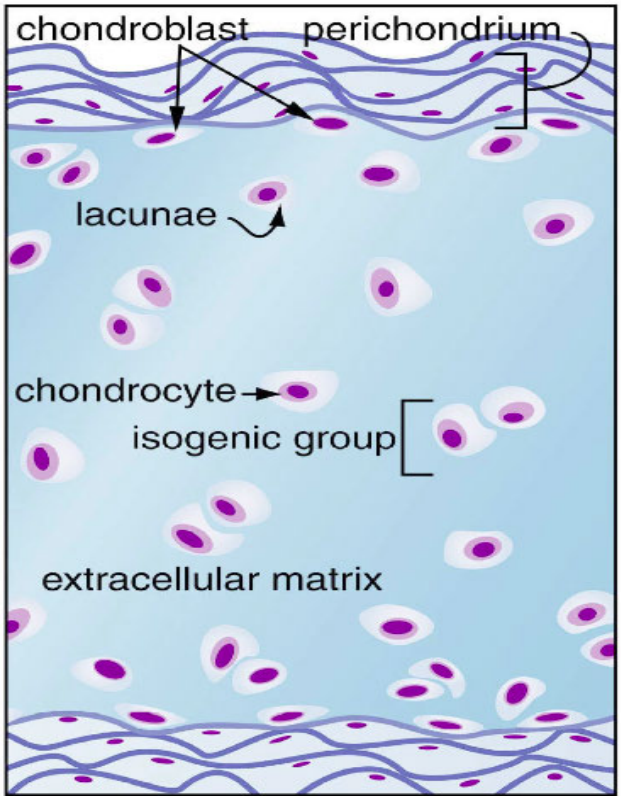


FIGURE 1. A. shows the histology of hyaline cartilage [22], and B. shows the schematic illustration of the hyaline cartilage. Figures clearly indicates the presence of characteristic extracellular matrix and embedded chondrocytes.

layer of the perichondrium contains collagen producing fibroblasts, and the inner layer contains chondroblasts.

III. CARTILAGE MODELING PROCESS

The similarities between tissue building blocks are more in biological functions and composition and less in their exact structure. Designing a realistic model to predict the dielectric permittivity of cartilage tissue does not require including all of its constituents. Only those components should be viewed which have a prominent effect on the dielectric permittivity of the tissue. The main goal of computational micro-macro tissue modeling is to figure out the relationships between the microstructure and the macroscopic response or ''structural property'' of the tissue.

The question to be answered in this paper is posed as follows: can we deduce a relationship between the electrical properties of an articular cartilage tissue and its constituent parameters that reflect its cellular arrangement? The parameters of our interest include the cell geometry, ground substance, and the extra cellular space. Based on Figure 1, the most important building blocks of articular cartilage are cartilage cells, also called chondrocytes, having approximately 10 μm diameter, and porous extracellular matrix consisting of water, collagen and proteoglycans. In this section, we define the following major constituents of our interest:

A. CHONDROCYTES

The cells that form the cartilage are called chondrocytes. The chondrocyte cells are originated from chondroblast cells. They are located through the tissue in scattered small cavities known as lacunae. The area immediately adjacent to the cell is called the capsule and stains intensely because of the rich glycosaminoglycan content. The number of chondrocyte cells created and their maturation process can be influenced by multiple different genes and proteins. The proportion of the chondrocytes in cartilage volume is about 1-5 % and their task is to synthesize the components of extracellular matrix and maintain cartilage metabolism. Unfortunately, chondrocytes have limited potential for replication [23].

Chondrocytes cells are responsible to produce the collagen extracellular matrix. They are surrounded completely by the matrix they produce. Chondrocytes vary in shape, number, and size, depending on the anatomical regions of the cartilage tissue. They are spherical or ellipsoidal cells with a correspondingly shaped central or eccentric nucleus with condensed chromatin. Chondrocytes in hyaline cartilage that are grouped together are called isogenic groups.

B. EXTRACELLULAR MATRIX

Cartilage extracellular matrix plays a critical role in controlling chondrocyte metabolism. It provides structural strength to tissues, maintaining a complex architecture around the

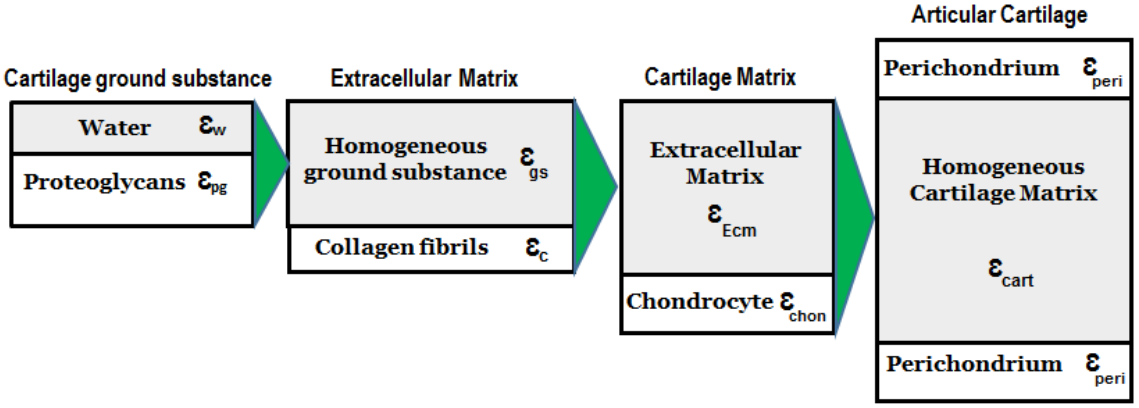


FIGURE 2. Cartilage is a connective tissue consisting of chondrocytes and a matrix of collagen fibers within a water-rich, gel-like ground substance (The hierarchy of scales).

cells and the shape of organs. It is composed predominantly of collagens, non-collagenous proteins (proteoglycans), lipids, phospholipids, and water molecules. Together, these components help to retain water within the extracellular matrix, which is critical to maintain its unique mechanical properties. The composition of the extracellular matrix as well as the organization of chondrocytes is dependent on the age of the tissue [20].

C. WATER

Water is the most abundant component of cartilage, accounting for 60–80% of the tissue weight. The load-bearing properties of cartilage result from its ability to retain water. The proteins in the cartilage absorb water which gives cartilage its ability to hold the shape of flexible body structures. The flow of water through the cartilage helps to transport nutrients to chondrocytes. Inorganic ions such as sodium, calcium, and potassium are dissolved in the tissue water [24].

D. COLLAGENS

Collagen is an essential component of cartilage. It is the most prominent structural macromolecule in the extracellular matrix. The solid fraction of the cartilage is composed of collagens (50–75%), proteoglycans (15–30%), and a minor amount of non-collagenous proteins [25]. A major component of the extracellular matrix is the protein collagen. Collagen proteins are modified with carbohydrates, and once they are released from the cell, they assemble into long fibers called collagen fibrils. Collagen fiber is a type of biological fiber that is characteristically white and composed of collagen. It is typically arranged in branching bundles of indefinite length [26].

E. PROTEOGLYCANS

Proteoglycans are a diverse group of proteins, grouped together solely because of their glycosaminoglycan content. Each proteoglycan serves several functions that are determined by both its core protein and its glycosaminoglycan chains. By binding to collagen these proteoglycans may regulate the thickness of collagen fibrils in matrices. They bind water giving a gel-like fluid helping to absorb compression and force [27].

The theoretical modeling of electrical properties for the tissue starts from the smallest scale. Considering such small scale, each of the constituents can be considered as homogeneous materials. Therefore, we could apply mixture rules and then proceeding to the next, larger scale, where one has the homogenized model of the previous step among other constituents of the larger scale. The process of applying mixture rules is then repeated as in the previous step. The mixing steps are schematically shown in Figure 2 for the cartilage tissue.

As a first approximation, biological tissues can be considered to take the form of an electrolyte containing densely packed cells. These cells encapsulated by thin membranes containing an intracellular fluid composed of various salt ions, proteoglycans and polar water molecules [28]. The ionic content is modeled by the addition of a conductivity term to the water model equation. We have used Cole-Cole expression to express the complex frequency-dependent dielectric properties of water:

$$\varepsilon_w = \varepsilon_\infty + \sum_{n=1}^{4} \frac{\Delta\varepsilon_n}{1 + (j\omega\tau_n)^{1-\alpha_n}} \tag{1}$$

Here, the Cole-Cole parameters are taken from [5] as: $\varepsilon_\infty = 4$, $\alpha_1 = 0.15$, $\alpha_2 = 0.15$, $\alpha_3 = 0.1$, $\alpha_4 = 0$, $\tau_1 = 1.326{*}10^{-11}$ sec, $\tau_2 = 1.447{*}10^{-7}$ sec, $\tau_3 = 3.183{*}10^{-4}$ sec, $\tau_4 = 1.592{*}10^{-2}$sec, $\Delta\varepsilon_1 = 38$, $\Delta\varepsilon_2 = 2500$, $\Delta\varepsilon_3 = 1.0{*}10^5$, $\Delta\varepsilon_4 = 4.0{*}10^7$. Hence, the given aqueous electrolyte permittivity $\varepsilon_{\mathrm{lyt}}$ is:

$$\varepsilon_{lyt} = \varepsilon_w + \frac{O_i}{j\omega\varepsilon_0} \tag{2}$$

where the parameter σ_{i} stands for ionic conductivity. The ionic conductivity is more important at lower frequencies.

TABLE 1. Model parameters for the articular cartilage tissue.

Symbol	Description	Value (Human)	Reference
d_{per}	Perichondrium thickness	471 µm	[32]
d_{mat}	Thickness of the matrix	1300-3200 µm	[20]
d_{cart}	Cartilage thickness	2– 4 mm	[18]
V_c	Collagen volume fraction in matrix	0.015 – 0.15	[29]
ε_c	Permittivity estimation for collagen	2.4	[33]
V_{pg}	Volume fraction of proteoglycans in ground substance	0.02 - 0.2	[34]
ε_{pg}	Permittivity approximation for proteoglycans in ground substance	3 (2-5)	[35]
V_{ch}	Mean volume fraction of chondrocyte in the extracellular matrix	0.09 – 0.13	[36]

Finally, the permittivity of the ground substance, (ε_{gs}), is then obtained by applying the Maxwell-Garnet (MG) mixture rule, which assumes spherical particles of proteoglycans (ε_{pg}) in a background of ε_{lyt} [29] and by using the volume fraction value, v_{pg}, as given in Table 1.

$$\varepsilon_{gs} = \varepsilon_{lyt} + 3v_{pg}\varepsilon_{lyt}\frac{\varepsilon_{pg} - \varepsilon_{lyt}}{\varepsilon_{pg} + 2\varepsilon_{lyt} - v_{pg}\left(\varepsilon_{pg} - \varepsilon_{lyt}\right)} \quad (3)$$

where the parameter, v_{pg}, is the volume fraction of proteoglycans in ground substance and (ε_{pg}) is permittivity approximation for proteoglycans in ground substance.

The cartilage extracellular matrix is composed of the aqueous ground substance and collagen fibrils as inclusions. The ability of cells to sense and respond to the applied electric fields is important. The electrical field vector is either perpendicular to the fibrils ($\varepsilon^{\perp f}_{matrix}$) or parallels the fibrils ($\varepsilon^{\| f}_{matrix}$). In case of perpendicular electric field, we could apply the MG mixture rule of cylindrical implication to estimate $\varepsilon^{\perp f}_{matrix}$. On the other side, the linear mixture rule of parallel-capacitors will be used to obtain $\varepsilon^{\| f}_{matrix}$ [30].

$$\varepsilon^{\perp f}_{\text{matrix}} = \varepsilon_{gs} + 2v_c\varepsilon_{gs}\frac{\varepsilon_c - \varepsilon_{gs}}{\varepsilon_c + \varepsilon_{gs} - v_c\left(\varepsilon_c - \varepsilon_{gs}\right)} \quad (4)$$

$$\varepsilon^{\| f}_{matrix} = \varepsilon_{gs}(1 - v_c) + v_c\,\varepsilon_c \quad (5)$$

where the parameter (v_c) is the collagen volume fraction in matrix and (ε_c) is permittivity estimation for collagen. We note that the structure of the cartilage tissue is anisotropic.

TABLE 2. Model parameters for the cellular components (perichondrium, chondrocytes).

Symbol	Description	Value (Human)	Reference
d_m	Thickness of the membrane	5.5 nm	[37]
d_{per}	Average cell diameter in the perichondrium	5 µm	[38]
d_{ch}	Chondrocytes thickness	10.63 µm	[25]
ε_m	Permittivity of lipid membrane models	9	[31]
ε_{cyt}	permittivity of the cytoplasm	See text	[31]

It is desired to calculate the effective dielectric tensor $\varepsilon_{effective}$

$$\varepsilon_{effective} = \begin{pmatrix} \varepsilon^{xx}_{matrix} & \varepsilon^{xy}_{matrix} & \varepsilon^{xz}_{matrix} \\ \varepsilon^{yx}_{matrix} & \varepsilon^{yy}_{matrix} & \varepsilon^{yz}_{matrix} \\ \varepsilon^{zx}_{matrix} & \varepsilon^{zy}_{matrix} & \varepsilon^{zz}_{matrix} \end{pmatrix} = \begin{pmatrix} \varepsilon^{\| f}_{matrix} & 0 & 0 \\ 0 & \varepsilon^{\| f}_{matrix} & 0 \\ 0 & 0 & \varepsilon^{\perp f}_{matrix} \end{pmatrix} \quad (6)$$

superscripts $\varepsilon^{\| f}_{matrix}$ and $\varepsilon^{\perp f}_{matrix}$ indicate direction parallel or perpendicular to linear collagen fibrils, respectively. Practically, the fibril orientations could appear periodically parallel or perpendicular to the applied electric field hence the effective permittivity of the extracellular matrix for both cases will be given as:

$$\varepsilon^{\| f}_{ECM} = \frac{1}{2}(\varepsilon^{\| f}_{matrix} + \varepsilon^{\perp f}_{matrix}) \quad (7)$$

$$\varepsilon^{\perp f}_{ECM} = \varepsilon^{\perp f}_{\text{matrix}} \quad (8)$$

Electron microscope images of chondrocyte cells show that the cytoplasm forms a very thin layer around a large spherical droplet. To model the chondrocytes dispersed throughout the cartilage extracellular matrix, the MG mixture rule for double layer spherical inclusions [23] is used. The volume fraction (v_{ch}) and membrane (ε_{m}) values are described in Table 2. The cytoplasm (ε_{cyt}) is modeled based on the frequency-dependent cytoplasm parameters from Gimsa *et al.* [31] and by using two term Cole-Cole expression with $\varepsilon_1 = 212$, $\varepsilon_2 = 50$, $\varepsilon_\infty = 4$, $\tau_1 = 10.61{*}10^{-9}$ sec, $\tau_2 = 7.2{*}10^{-12}$ sec, $\alpha_1 = 0.5$, $\alpha_2 = 0$, and $\sigma_{\text{i}} = 1\ \text{Sm}^{-1}$. Letting ε_{mc} denote the complex permittivity of the extracellular matrix with chondrocytes (9) and (10), as shown at the bottom of the page, where the parameter (ε_m) is the permittivity of lipid membrane, (v_{ch}) is the mean volume fraction of chondrocyte in the extracellular

$$\frac{\varepsilon_{mc} - \varepsilon_{ECM}}{\varepsilon_{mc} + \varepsilon_{ECM}} = v_{ch}\frac{(\varepsilon_m - \varepsilon_{ECM})(\varepsilon_{cyt} + 2\varepsilon_m) + w(\varepsilon_{cyt} - \varepsilon_m)(2\varepsilon_{ECM} + 2\varepsilon_m)}{(\varepsilon_m + 2\varepsilon_{ECM})(\varepsilon_{cyt} + 2\varepsilon_m) + 2w(\varepsilon_{cyt} - \varepsilon_m)(\varepsilon_m - \varepsilon_{ECM})} \quad (9)$$

$$w = \left[(R - d_m)/R\right]^3 \quad (10)$$

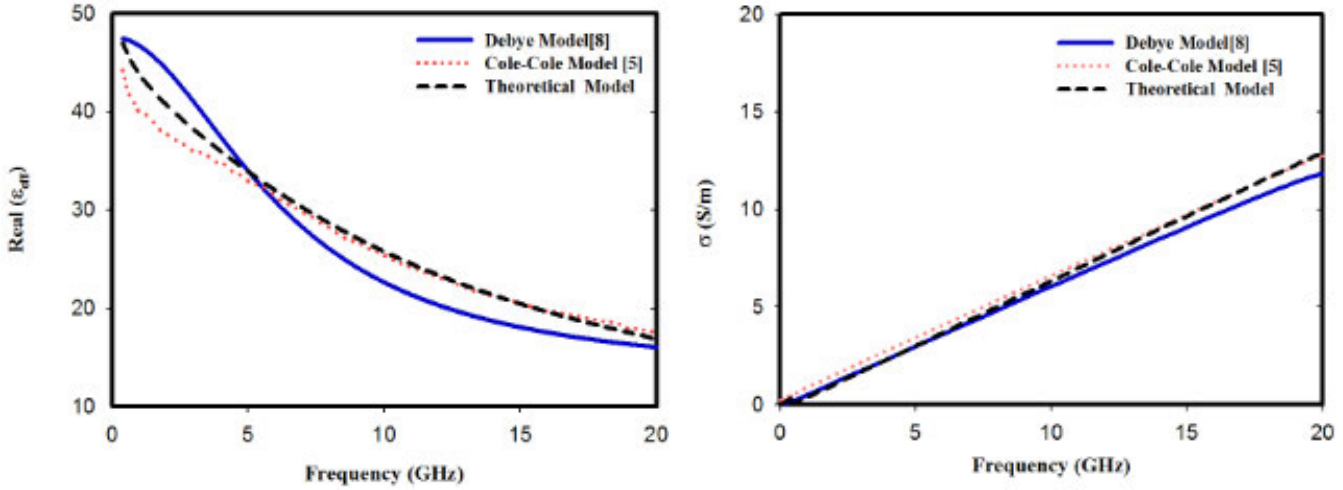


FIGURE 3. Theoretical model for the cartilage tissue compared to measured data from [5], and [8].

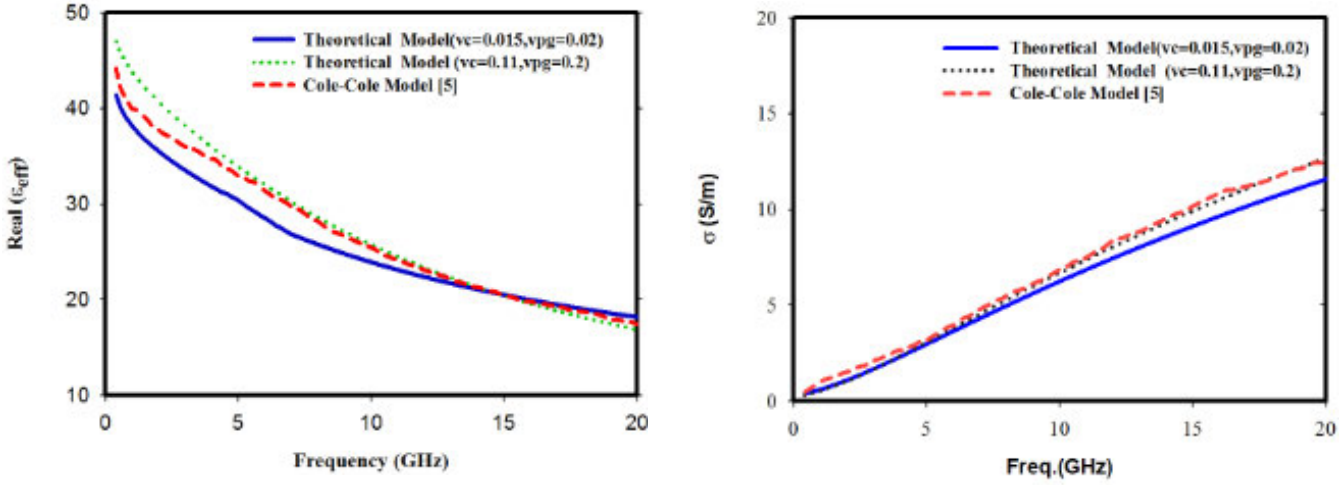


FIGURE 4. Effect of changing the volume fraction of cartilage composition as a function of frequency compared to measured data from [5].

matrix, and (ε_{cyt}) is the permittivity of the cytoplasm with R denoting the cell radius and d_{m} the membrane thickness. Both $\varepsilon_{mc}^{\|f}$ and $\varepsilon_{mc}^{\perp f}$ will be obtained, if ε_{ECM} is substituted by $\varepsilon_{EMC}^{\|f}$ and $\varepsilon_{EMC}^{\perp f}$, respectively. In the model hierarchy, the matrix layer has to be found between the perichondrium layers. The parameter $N_{\mathrm{m}} = 4$ is the number of membrane layers

$$\varepsilon_{cart}^{\perp f} = \left(2d_{per} + d_{ECM} + N_m d_m\right)\left(\frac{2d_{per}}{\varepsilon_{cyt}} + \frac{N_m d_m}{\varepsilon_m} + \frac{d_{ECM}}{\varepsilon_{mc}^{\perp f}}\right)^{-1} \tag{11}$$

where the parameter, d_{per}, is perichondrium thickness. The permittivity of perichondrium layer is calculated by a series-capacitance rule

$$\varepsilon_{per} = \left(d_{cyt} + 2d_m\right)\left(\frac{d_{cyt}}{\varepsilon_{cyt}} + \frac{2d_m}{\varepsilon_m}\right)^{-1} \tag{12}$$

where the parameter, d_{cyt}, is the cytoplasm thickness. Finally, the whole effective permittivity of the cartilage tissue is given by

$$\varepsilon_{cart}^{\|f} = \frac{2\varepsilon_{per}d_{per} + \varepsilon_{mc}^{\|f}d_{mat} + N_m d_m \varepsilon_m}{2d_{per} + d_{mat} + N_m d_m} \tag{13}$$

where the parameter, d_{mat}, is the thickness of the matrix.

IV. RESULTS AND DISUCSSION

In biological systems, a perfect measurement does not always exist. The change in water content of tissue samples that are frozen and defrosted before the measurement will affect the accuracy of the measured data. Small deviations from the true value will lead to an error in the prediction of the complex permittivity at higher microwave frequencies. Furthermore, the collected experimental data tend to have larger inaccuracies with increase in frequency due to the

increased complexity of the measurement. Therefore, our main goal in this manuscript is to come up with a realistic model for an articular cartilage tissue that exhibits the dielectric characteristics expected from both measurements and predicted data based on relaxation models. One of the advantages of the theoretical model is its independence from measurements; it is not a mathematical expression fitted to experimental data, but rather a physics-based bottom-to-top method for theoretically reproducing a set of tissue properties over a wide range of frequencies. This theoretical model could be used for predicting the dielectric properties of cartilage tissues at higher frequencies which are needed for computational dosimetry, and some ophthalmological applications.

Limited comparative data, given in literature, are available on the dielectric behavior of cartilage. Based on the previous equations, the cartilage tissue permittivity and conductivity are computed and then compared with fitting data of two different dispersion models (i.e., Cole-Cole and Debye models) that are barely available in literature. In Figure 3, we present the results of the whole effective permittivity of the cartilage tissue, $\varepsilon_{cart}^{\|f}$, corresponds to the case of parallel electric field polarization. It is observed that our proposed model reproduces the predicted data of Cole-Cole model above several hundred MHz fairly well. The Debye model shows some variations with the Cole–Cole model in the microwave region. However, the deviations are observed within an acceptable range of standard error of $\pm$ 5%. This may be due to that the dielectric behavior is affected by water content and blood infiltration within the tissue. Also, the difference in tissue sample composition is another factor for these variations.

Functionally, the most important aspect of cartilage composition is its collagen volume fraction in extracellular matrix [20]. Proteoglycans are another important component of the extracellular matrix [19]. The volume fraction of proteoglycans in the ground substance is also influencing the electric properties of the tissue. Factors relating to the organization of the extracellular matrix macromolecules (e.g., various types of collagen and proteoglycans), and of the heterogeneous cellular and compositional distributions within the tissue also play significant roles in defining and controlling the electric properties of the articular cartilage [26].

According to Table 1, the collagen volume fraction has values ranging from a low of 0.015 to a high of 0.15 and the collagen volume fraction has values ranging from a low of 0.02 to a high of 0.2. The permittivity and conductivity of the cartilage tissue is obtained for the lowest and greatest values of each range to emphasize the verification and analysis of the model sensitivity to input parameters. The effect of the variation of the volume fraction of collagen and proteoglycans on the electric properties is studied in Figure 4 and the results indicate that the variations in the volume fraction of either of them have a remarkable effect on both of permittivity and conductivity of the tissue.

V. CONCLUSION

The ability to deduce a theoretical model that accurately reproduces the microanatomy of the native tissue is a challenging object of research. In this study, we have developed a novel analytical macro-structural model for human cartilage tissues. Our ultimate goal is devoted to understand and develop a realistic model for cartilage tissues that exhibits the dielectric characteristics expected from real measurements or predicted data from relaxation models at higher frequencies. The proposed model possesses microanatomical features reminiscent of a native tissue. We succeeded to investigate the dielectric properties of the cartilage tissue based on its physical composition and by applying appropriate mixing rules to the microstructure of the tissue in several steps. It is shown that the particular composition and arrangement of the extracellular matrix can influence the dielectric properties of the tissue. The model has been validated in the microwave band showing a good agreement to obtained data in literature. This model platform will be of significant interest to scientists researching the structure and function of human cartilage.

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