1. Introduction

The interaction of an electromagnetic (EM) field with a biological system vastly depends upon the electrical properties of that system. Therefore, a precise understanding of tissue electrical properties in biomedical applications of EM radiation is crucial.[1] The electrical properties to be presented in this paper include the conductivity, $\sigma$, dielectric permittivity relative to free space, $\varepsilon_r'$, and the loss tangent, $\tan \delta$. The conductivity is related to the free-path length and speed of the electrons inside the material, and is defined as the conductance of a unit volume of matter. The dielectric permittivity is the capacitance of a unit volume of matter, divided by the permittivity of free space $\varepsilon_0^1$. The complex permittivity is defined as: $\varepsilon^* = \varepsilon' - j\varepsilon''$, where the real part, $\varepsilon'$, is the permittivity and conventionally expressed relative to the permittivity of free space by the relative dielectric constant, $\varepsilon'_r = \varepsilon' / \varepsilon_0$. The imaginary part of the complex permittivity is called the loss factor, which can also be expressed relative to the free space permittivity as $\varepsilon''_r = \varepsilon'' / \varepsilon_0$. The loss tangent is simply the ratio $\tan \delta = \varepsilon'' / \varepsilon'$. The conductivity $\sigma = \omega \varepsilon''$, where $\omega = 2\pi f$ is the angular frequency and $f$ represents the frequency of the EM field in hertz.[1][2]

2. Tissue Electrical Properties

Electrical properties of a tissue are a direct consequence of its composition and structure, and basically describe how the tissue interacts with EM energy. In tissues, an EM field primarily acts upon components within the material with a net electrical charge and/or an electric dipole moment.[3] An electric current flow within the material in consequence of the transmitted motion to these components. In biological tissues, ions,

$^1 \varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$
such as Na+, Cl-, K+, and Ca2+, possess a net electrical charge, and polar molecules, such as water, in addition to protein structures, muscle, fat, and bulk, are the main source of electrical dipole moments.[4] Since there is a wide variety of components that determine the electrical properties of a tissue, these properties can be significantly affected by variations in temperature, frequency, tissue type, and vascularization. In turn, these variations in electrical properties of the tissue can be useful to measure different physiological conditions.[1]

Several investigations of in-vitro tissue dielectric properties in the frequency range from 1 Hz to 30 GHz suggest the existence of three dispersion regions in tissue dielectric properties. Schwan entitled these regions the $\alpha$, $\beta$, and $\gamma$ dispersion regions and related the dispersion phenomena to various tissue components.[4] The $\alpha$-dispersion region (0.1-100 kHz) results from the frequency dependence of the outer-cell membrane impedance. There are several factors that may cause this membrane impedance frequency dependence such as: a frequency-dependent access to inner membrane systems (mitochondrial membrane), a frequency-dependent outer membrane conductance, a boundary potential-related series capacitance element, and a frequency-dependent membrane capacitance due to ionic gating currents. The permittivity decreases with the alpha dispersion. Since cellular membranes enclose bound water, they act as insulating structures. The $\beta$ dispersion (1-20 MHz) is due to the presence of these membranes. Bound water is the water bound to macromolecules, usually proteins. When the EM frequency increases, the cellular membranes are short-circuited. i.e. bound water insulating effects of the cellular membranes decreases. The beta relaxation is responsible for the next decrease in permittivity. Moreover, since the conduction through the cell membrane increases, the conductivity increases as well. Gamma relaxation, $\gamma$, occurs near 20 GHz, and is mainly due to the dipolar relaxation of water in the tissues. Between the $\beta$ and $\gamma$ dispersion regions, there is another dispersion, known as $\delta$ dispersion, which is ranged from a few hundred MHz to several GHz.[5] Several investigations of tissue electrical properties have verified that the electrical properties of different tissues, such as blood, muscle, and fatty tissues, in microwave frequency range are determined primarily by their water and electrolyte content.[6][7]. Because of the important role of water in electrical properties of tissues, tissues are sometimes classified into two
categories: (1) muscle, blood, brain, and the internal organs with high water content, and (2) fat, bone, lung, and the outer layer of skin with low water content. Low water content tissues have lower permittivity values than high water content tissues. Figure 1 shows how water content in tissue is a major factor in determining permittivity and conductivity:

![Figure 1](image1)

**3. Tissue Dielectric Property Measurement**

Dielectric property measurement techniques are based on measuring the effects of the interaction of tissue with an EM field at a specific frequency. One of the most used techniques utilizes a section of open-ended coaxial cable that is placed in contact with a sample of the material being measured. Figure 2 illustrates the basic configuration of *in-situ*\(^2\) dielectric measurement probe.

![Figure 2](image2)

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\(^2\) *In situ* is a Latin phrase meaning in the place. In biology, in situ usually means something intermediate between in vivo and in vitro. (Definition from Wikipedia)
Network analyzer measures the relative amplitude and phase difference between the reference and reflected signal channels, which determines the terminal impedance of the probe based on the magnitude and phase angle of the reflection coefficient. Then, these data are input to a computer algorithm to compute the dielectric property information after correcting systemic measurement errors.[1]

4. Measured Tissue Dielectric Properties (results)

A number of studies have been done with the goal of measuring electrical properties of normal and malignant tissues. In 1994, Joines et al. measured the dielectric properties of several tissues in vitro.[11] Over the frequency range between 50 and 900 MHz, they measured the relative permittivity and conductivity of normal and malignant tissues including: colon, kidney, liver, lung and mammary gland. Supposing that the malignant tissue is modeled as a sphere (small compared to wavelength) surrounded by an infinite medium of host normal tissue, they calculated the ratio of the power absorbed in the malignant tissue ($P_m$) to that absorbed in the normal tissue ($P_n$) using the following equation:

$$\frac{P_m}{P_n} = \frac{9(\sigma_m/\sigma_n)^2}{(2 + \epsilon_m/\epsilon_n)^2 + (2 + \sigma_m/\sigma_n^2)(\sigma_n/\omega\epsilon_n)^2}$$

where $m$ and $n$ refer to malignant and normal tissues, respectively. Using the measured values of relative permittivity and conductivity for normal and malignant human tissues in the equation above, $P_m/P_n$ was calculated and plotted. (Figure 3).

![Figure 3](image-url)
As illustrated in Figure 3, the largest difference in the measured electrical properties occurred for mammary tissue. Because of higher water content in malignant tissues comparing to normal tissues, malignant tissues have higher than normal electrical properties. In 2000, a clinical prototype of a microwave tomographic system for breast imaging (in vivo) was reported by Meaney et.al.[12] Their results confirmed a contrast between normal and malignant breast tissue close to 2:1. In 2002, Sha et.al. analyzed the dielectric properties of normal and malignant breast tissue at a wide range of frequencies.[13] They reported the diagnostic value of the dielectric properties from the data provided by several investigation groups as:

- The low conductivity values of the normal breast tissue enable penetration of microwave frequencies up to the low GHz range.
- At 100 MHz – 1 GHz, dielectric properties can significantly help classify normal and malignant tissues.

Using previous studies, they also reported a variety of factors that lead to a significant difference in dielectric properties of normal and malignant tissues, especially in breast. [13]:

- **Necrosis**: Inflammation and necrosis are commonly found in malignant breast tissues. As a result of presence of necrosis, cell membranes break down and thus, a larger portion of the tissue is able to carry current at low frequencies, which decreases the capacitance of the tumor.[14][15]

- **Charging of the cell membrane**: In breast carcinoma, fat lobules are gradually replaced by fibroblastic proliferation and epithelial cells. Cancer cell have reduced membrane potentials and their ability to absorb positive ions is altered. Consequently, they have a higher negative surface charge on their membrane.[16] According to Joines et.al., this alteration cause an increase in conductivity of the malignant tissue.[17]

- **Relaxation times**: The relaxation times in malignant tissue are larger than those in normal tissues. This fact indicates a considerable increase in the motional freedom of water.[16] Surowiec et.al., verified that the average dielectric relaxation time in cancerous breast tissues is significantly larger (between 0.6 and 1.4 μs) than in surrounding normal tissues (0.3 μs).[18]
• **Sodium concentration and water content:** The sodium concentration in tumor cells is higher than in normal cells.[16] Increased sodium concentration not only effects the cell membrane potential, but also makes malignant tissue retain more fluid in the form of bound water, which has larger values of conductivity and permittivity. Malignant breast tissue has a higher ratio of water content compared with that of the normal tissue, which results in higher dielectric properties than normal breast tissue at the same microwave frequency.

5. **Active Microwave Imaging**

So forth, we have seen the strongest motivation for using active microwaves (ranging from high MHz to low GHz) to detect abnormalities in the breast: Dielectric properties of normal and malignant human breast tissue differ significantly over the microwave frequency range above. Indeed, the largest difference in dielectric properties of various normal and malignant tissues occurs in mammary glands. In addition, since the breast is mainly composed of fat, active microwaves can easily penetrate in the tissue. Moreover, easy accessibility and relative small size of the breast make microwave imaging an attractive technique to detect breast cancer.

The basic idea of microwave imaging is illustrated in Figure 4. A transmitter is used to illuminate the breast with microwaves, and several receivers detect the transmitted signal. In presence of tumor (Figure 4b), the transmitted signal that hits the tumor gets distorted because of different dielectric properties of the tumor. As a result, the amounts of EM energy received at receivers changes. These changes are reflected in reconstructed images formed from detected information received at receivers.[9]
6. Breast Microwave Imaging at Dartmouth College

Figure 5 shows the basic setup of a clinical microwave imaging system at Dartmouth College for detecting breast cancer.

This system consists of an array of 16 monopole antennas inserted into a tank from the lower plate. The tank is filled with a coupling liquid (a mixture of 80% or 86% glycerine, and 20% or 14% water) to provide very similar electrical properties to those of the breast. The patient lies prone on the examination table with the breast to be examined suspended through an aperture into the tank, as is shown in figure 6.

During the acquisition of data, the antenna array can move up and down by a computer-controlled linear actuator to scan the breast in multiple vertical positions (7 planes by default). Each antenna acts as both transmitter and receiver. At each position
and at each time, one antenna transmits a signal in a specific frequency, while the remaining 15 antennas measure the scattered signal. This results in 240 measurements of the scattered field for each plane, and the process is repeated for all 7 positions over the frequency range starting from 500 to 2500 MHz with usually 200 MHz increasing steps. Finally, the images are reconstructed using Gauss-Newton iterative algorithm in addition to some regularization method.

7. Conclusions and Future Works

Microwave imaging is becoming a promising new technique for detecting breast cancer. Even though it is not expected that microwave imaging will replace other used techniques to detect the breast cancer, such as X-ray mammography or MRI, microwave imaging can be used in combination with other techniques to improve cancer detection. Microwave imaging for detecting breast cancer can also be used for young women for whom mammography is not recommended as a helpful and safe diagnostic tool. Having said this, there is still an enormous amount of research and development to be completed in order to obtain a reliable performance.

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9. References: