2.2 Dielectric Properties of Biological Tissues

2.2.1 Basic Definitions

The charge carriers (positive and negative) inside atoms and molecules (groups of atoms) can be displaced if an external electric field is applied [133]–[135]. The displacement effect is called polarisation and it is due to the interaction of an electric field with a material [135], [136]. An atom or a molecule in a material can have a positive or a negative charge when the number of electrons is not equal to the number of protons in that atom or molecule [135]. Such charged atoms or molecules are called ions. For a material that has ions, the external electric field also causes charge drift which results in charge conduction and ionic currents [133], [134].

Biological materials are dielectric in nature. A dielectric material can be polarised by an applied electric field. In the case of an applied external electric field, the electric charges in the dielectric material slightly shift from their average equilibrium positions causing the dielectric polarisation [134]. Biological materials contain both free charges (ions) and bound charges (polar molecules) [137], [138]. Therefore, an external electric field will have two effects on the biological materials: 1) the field will trigger several polarisation mechanisms, each governed by its own time constant, and 2) the field will also cause ionic drift [133], [134]. Thus, the overall result of an applied electric field would be the establishment of both displacement and conduction currents.

The interaction of the EM field with a dielectric material is governed by the dielectric properties of the material, namely the complex permittivity [139], [140].

1.2 REVIEW OF POLAR DIELECTRIC BEHAVIOUR

1.2.1 Dielectrics

Propagation of electromagnetic waves in materials such as dielectrics and conductors is determined by their electrical parameters. In the case of dielectrics, chief amongst these is the complex permittivity, ε, of the dielectric material which describes its ability to support an electric field. An electric field results from a potential difference supported across a medium and is therefore not possible within a pure conductor. Free space has dielectric properties by virtue of the energy temporarily borrowed to create short lived virtual charges to support an electric field. Many other dielectrics exhibit phenomena which also contribute to their permittivity such as the ability to support current flow (both ionic and displacement currents) and molecular polarisation. It is normal to refer to the *relative permittivity*, ε_r, of a dielectric as being its permittivity with respect to that of free space, ε_0, such that:

$$\varepsilon = \varepsilon_r . \varepsilon_0 \qquad (1.1)$$

The relative permittivity of a dielectric is defined as the factor by which the capacitance of a capacitor increases when the volume between and around its plates is filled with the dielectric as compared with free space. It is known that the permittivity of a dielectric is determined by its molecular/atomic structure but no theory exists to relate the two. It is also known that permittivity is often (but by no means always) frequency and temperature dependent, since certain phenomena which determine its permittivity are functions of frequency and temperature. Furthermore, the permittivity differs for the various phases of the material which is unsurprising since the concentration of particles and their bonding differs in each phase. Various theories have been proposed to describe the permittivity of mixed dielectrics from its constituent ingredients, concentration and particle size and shape. These have been useful in describing the behaviour of solutions, suspensions and complex structures of dielectrics.

In a time-varying field, assuming linear, isotropic behaviour, the complex permittivity of a biological material can be expressed as:

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \tag{2.8}$$

where ε' and ε'' are the real and the imaginary parts of the complex permittivity, respectively, $j = \sqrt{-1}$ and $\omega = 2\pi f (rad/s)$, f is the frequency of operation with units: Hz. The real part of the complex permittivity is also known as the dielectric constant or the relative permittivity (in this dissertation, the terms dielectric constant and relative permittivity are used interchangeably). The relative permittivity, ε', is a measure of the ability of the material to store electric energy, and is expressed as a ratio of the complex permittivity, ε, to the permittivity of free space, $\varepsilon_0 = 8.8541 \times 10^{-12} Fm^{-1}$.

The imaginary part of the complex permittivity, ε'', is also known as the dielectric loss and is zero for lossless materials. The dielectric loss is a measure of the amount of energy dissipated in the material due to an external electric field [143]. The dielectric loss can be converted into the effective conductivity of material, σ (Sm^{-1}), as follows:

$$\sigma(\omega) = \omega\varepsilon_0\varepsilon''(\omega). \tag{2.9}$$

The ratio of the imaginary part to the real part of the complex permittivity is called the loss tangent, $tan\ \delta$, and is expressed as:

$$tan\ \delta = \frac{\varepsilon''}{\varepsilon'}. \tag{2.10}$$