AN INVESTIGATION ON PROPAGATION AND ABSORPTION OF ELECTROMAGNETIC SIGNALS THROUGH BIOLOGICAL MEDIA

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Abstract

A basic knowledge of biological material properties, their uniqueness, and their variability among living systems may provide a basis for the exploitation of electromagnetic interaction mechanisms. The macroscopic approach deals with the whole biological material exposed to electromagnetic fields generated by the exogenous fields. This approach requires complete knowledge of the electromagnetic properties of the material. Ability to solve Maxwell's equations with the appropriate boundary conditions is also required.

A mathematical analysis of the processes of propagation and absorption of electromagnetic signals in the live tissues have been done in the paper taking in account some specific values of the conductivity of biological materials σ *, the real part of the complex relative permittivity of biological materials* ε' *and the imaginary part of the complex relative permittivity of biological materials* ε'' *.*

The principal results of present investigation is connected with mathematical description of the processes of propagation and absorption of electromagnetic signals in the live tissues.

1. Introduction

It’s known [1], [2], [3] that when electromagnetic radiation contacts matter, it interacts with atoms in the medium and behaves like particle in a way and like a wave in another way. Particle-like behaviors include reflection, scattering and absorption [4]. The wavelike behaviors include reflection, refraction, transmission, diffraction and absorption of electromagnetic signals [5], [6], [7]. The effect of the radiation on matter depends on many factors including wavelength components of radiation, the sending medium, the polarization components of the radiation and the angle of incidence [8], [9]. A mathematical analysis of propagation of electromagnetic signals through biological media is described in the paper.

2. Propagation of electromagnetic signals through biological media

The propagation of electromagnetic waves in a biological medium Figure (1) can be studied mathematically by solving Maxwell's equations under appropriate boundary conditions.

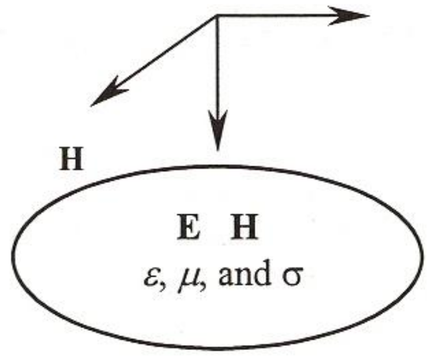

Figure 1. A biological body under EM radiation

These equations are very powerful, but complicated and difficult to solve. For simplicity, it's possible to assume that a biological medium is infinite in extent, source-free, isotropic, and homogeneous. The medium is isotropic if ε is a scalar constant, so **D** and **E** are the same in every direction. A homogeneous medium is one for which ε, μ and σ are constant. For this case, Maxwell's equations become:

$$\nabla x\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (1)$$

$$\nabla x\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad (2)$$

$$\nabla .\vec{B} = 0 \qquad (3)$$

$$\nabla \vec{D} = 0 \qquad (4)$$

Further, since the medium is assumed to be isotropic, its permittivity, permeability, and conductivity are scalars. In case the medium is homogeneous, these parameters are constants.

In order to solve this set of simultaneous equations for the vectors **E** and **H**, the vector **H** may be eliminated from the equation in the following way:

$$\nabla x(\nabla x\vec{E}) = -\mu\frac{\partial}{\partial t}(\nabla x\vec{H}) =$$

$$= -\mu\frac{\partial}{\partial t}(\sigma\vec{E} + \varepsilon\frac{\partial \vec{E}}{\partial t}) =$$

$$= -\mu\sigma\frac{\partial \vec{E}}{\partial t} - \varepsilon\mu\frac{\partial^2 \vec{E}}{\partial t^2} \qquad (5)$$

Using the vector identity, the equation determining the vector **E** comes out to be

$$\nabla x\nabla x\vec{E} = \nabla(\nabla .\vec{E}) - \nabla^2\vec{E} \qquad (6)$$

and using Equation (4):

$$(\nabla^2 - \mu\sigma\frac{\partial}{\partial t} - \mu\varepsilon\frac{\partial^2}{\partial t^2})\vec{E} = 0 \qquad (7)$$

Similarly, by eliminating E from the Maxwell's equations, it may shown that H satisfies the equation:

$$(\nabla^2 - \mu\sigma\frac{\partial}{\partial t} - \mu\varepsilon\frac{\partial^2}{\partial t^2})\vec{H} = 0 \qquad (8)$$

In view of the fact that equations governing **E** and **H** in the biological material (Maxwell's equations) are linear and keeping in mind that any arbitrarily time-varying function can be expressed as a sum of number of sinusoidal functions, time dependence of the fields, **E** and **H**, can be given by the factor $e^{j\omega t}$ so that

$$\frac{\partial}{\partial t} \equiv j\omega \text{ and } \frac{\partial^2}{\partial t^2} \equiv -\omega^2$$

Using both relationships in Equation (7), the wave equation becomes:

$$\nabla^2\vec{E} + \gamma^2\vec{E} = 0 \qquad (9)$$

where:

$$\gamma^2 = \omega^2\mu\varepsilon - j\omega\mu\sigma =$$

$$= \omega^2\mu\varepsilon_0(\varepsilon' - j\frac{\sigma}{\omega\varepsilon}) = \frac{\omega^2}{c^2}(\varepsilon' - j\varepsilon'') \qquad (10)$$

where:

σ is conductivity of biological materials;

ε' is the real part of the complex relative permittivity of biological materials;

ε'' is the imaginary part of the complex relative permittivity of biological materials;

ε_0 is the absolute permittivity

$$\varepsilon'' = \frac{\sigma}{\omega\varepsilon_0}$$

c is the free space velocity ($3x10^8\ m/s$) and γ is the propagation constant. This is, in general, a complex quantity and may be written in the form

$$\gamma = \alpha + j\beta \qquad (11)$$

where the attenuation constant is:

$$\alpha = \frac{\sqrt{2}c}{\omega\sqrt{\varepsilon'}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right)^{1/2}} \qquad (12)$$

for $\frac{\varepsilon''}{\varepsilon'} \le 1$:

$$\alpha = \frac{\omega\sqrt{\mu\varepsilon}}{\sqrt{2}}\left(\frac{\varepsilon''}{\varepsilon'}\right) \qquad (13)$$

and the phase constant in radians per meter is

$$\beta = \frac{\sqrt{2}c}{\omega\sqrt{\varepsilon'}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)^{1/2}} \qquad (14)$$

for $\frac{\varepsilon''}{\varepsilon'} \le 1$

$$\beta = \omega\sqrt{\mu\varepsilon}\left(1+0{,}125\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right) \qquad (15)$$

Using Equation (15), the wavelength λ can be determined by

$$\lambda = \frac{2\pi}{\beta} \qquad (16)$$

If the incident wave is a linearly polarized uniform plane wave traveling along the z-direction, then Equations (7) and (8) are of the form:

$$\vec{E} = E_i e^{-\alpha z} e^{j(\omega t-\beta z)}\vec{i}_x \qquad (17)$$

$$\vec{H} = H_i e^{-\alpha z} e^{j(\omega t-\beta z)}\vec{i}_y \qquad (18)$$

where $\left|\vec{E}_i\right| = \eta\left|\vec{H}_i\right|$

The intrinsic impedance of biological material η is given by

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}\left(1-0{,}378\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 + j0{,}5\left(\frac{\varepsilon''}{\varepsilon'}\right)\right) \qquad (19)$$

The Poynting vector, that is, the power flowing per unit area of cross section (W/m^2), gives the power density associated with an EM wave can be calculated:

$$P_i = \frac{\left|\vec{E}_i\right|^2}{2\eta} \qquad (20)$$

3. Absorption of electromagnetic signals in the biological materials

It's well known that at radio frequencies, biological tissues behave like solutions of electrolytes that contain polar molecules. RFR interacts with biological systems by way of ionic conduction (oscillation of free charges) and rotation of polar molecules of water and protein relaxation. Absorbed RF energy is transformed into kinetic energy of molecules, which is associated with a rise in temperature of the irradiated tissues.

In order to understand the factors influencing the rise in body temperature due to RF absorption, it is useful to study the different heat pathways within the body. The heat may be transferred to the environment only after it is first transferred to the body surface. This heat transfer may be accomplished by three mechanisms: thermal conduction, thermal radiation, convection, and sweat evaporation.

Thermal conduction is the process in which heat transfer takes place by molecular diffusion. The amount of heat energy flowing per second per unit area is proportional to the temperature gradient. Body tissues are quite poor thermal conductors with values of conductivity between 2-10 cal/min/m/°C.

Thermal radiation is the heat loss due to radiation from the surface of the human body.

Convection is the process in which heat is transferred by the simultaneous action of molecular diffusion and mixing motion.

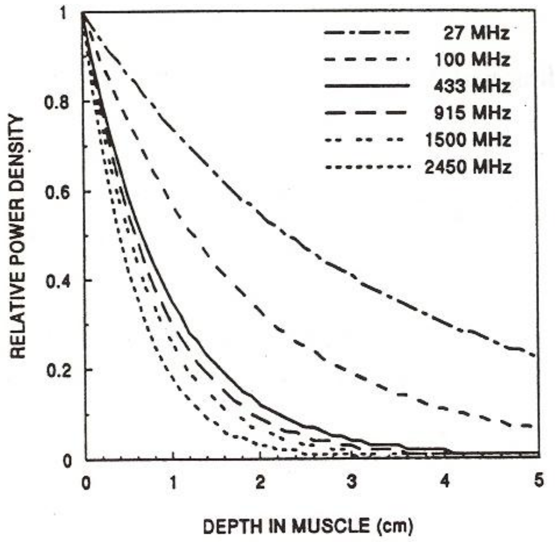

Figure 2. Power absorption in muscle as a function of depth at different frequencies

Evaporation is the heat loss due to evaporation at the surface per unit area (including sweat and insensible perspiration), and it depends on the arterial blood flow, the wind speed, and the humidity.

Sweating is controlled by the central neural integrative mechanism, which receives signals from the thermosensitive sites within the body.

Temperature differences, which would exist in the absence of blood flow, are equalized by the blood flow. The blood flow also controls the effective body insulation through constriction expansion of the cutaneous capillaries, so that the distance the heat has to flow through the superficial layer to the superficial epidermis increases or decreases accordingly.

A nonuniform distribution of absorbed power is a well-established fact [ ], which may lead to involved interactions. In some exposure situations, only certain parts of the body are absorbing RF power causing nonuniform heating, which is generally referred to as hot spots.

It is observed from Equation (17) and (18) that the wave gets attenuated as it propagates in the biological material along the z-axis. As shown from Figure 2, at a given depth uses of lower frequency results in a higher power density. It is also clear that a given power density is achieved at a greater depths in the muscle than that for a higher frequency. Not shown in Figure 2 is that penetration depth at about 30 GHz and higher is largely confined to the outer layers of the skin (much like for sunlight).

The energy is transferred from the applied E field to the material in the form of kinetic energy of charged particles. The rate of change of the energy transferred to the material is called the absorbed power. This power is also called power transferred, but from the bioelectromagnetics point of view, the term specific absorption rate (SAR) is the preferred one. SAR is a quantity properly averaged in time and space and expressed in watts per kilogram (W/kg). SAR values are of key importance when validating possible health hazards and setting safety standards

For steady-state sinusoidal fields, the time-averaged absorbed power per unit volume P_α is given by

$$P_\alpha = \sigma \left| \vec{E} \right|^2 \qquad (21)$$

where $\left|\vec{E}\right|$ is the root-mean-square (RMS) magnitude of the **E**-field at certain point in the material. To find the total absorbed power in a material, the power calculated from Equation (21) must he calculated at each point inside the body and integrated over the volume of the body. Figure 2 shows power absorption in muscle by a plane wave as a function of depth at different frequencies.

4. Conclusion

1. A mathematical analysis of propagation and absorption of electromagnetic signals through the biological media is described in the paper.

2. Some important equations (12), (15) and (19) have been obtained in the paper.

3. The obtained theoretical conclusions can be used as the base conclusion for the next investigation on SAR.

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