Numerical Simulation of Inductive Phase Shift Due a Brain Hematoma

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Abstract—We show a theoretically electromagnetic induction method to detect the changes of fluid volume into an organic tissue. This method is technique to detect a phase shift through measurements of induced electrical currents due a RF signal. This method was designed for volumetric brain edema monitoring. Circular and planar magnetron coils were evaluated and compared for their ability to detect edema in the brain through volumetric inductive phase shift spectroscopy. The circular coil was considered as a single turn wire and the magnetron surface coil configuration was based on the principle of the cavity magnetron with successive slots. The brain cavity was modeled as an idealized sphere transversely centered with respect to the coils. The volumetric sensitivity to changes in the brain was examined by inserting in the brain cavity a spherical edema/haematoma. Spectra of inductive phase shift induced in a second circular or magnetron receiver coils were estimated between frequencies from 100 kHz to 50 MHz. Phase shift shows sensitivity to the presence of the edema/haematoma increased with frequency. The use of a planar magnetron as the receiver coil produced a substantial increase in sensitivity, in particular at higher frequency of 50 MHz.

1. INTRODUCTION

Trauma to the head may result in the accumulation of liquids or blood in certain region of the brain. Edema is a medical condition in which the relative amount of liquid in tissue or organs increases. Haematoma is a pathological condition in which accumulation of blood occurs in a specific region. The characteristic of brain edema/haematoma is that it develops in a delayed and gradually progressive fashion after a head trauma or event has occurred, over a period of hours or days, and is a cause of substantial mortality [1]. Detection of edema/haematoma in the brain is essential for assessment of the medical condition and treatment. Because the complex electrical properties of edema/haematoma are substantially different from a hose of normal tissue, various measurements of electrical properties of the brain where proposed to non-invasive detect the changes in there [2–6].

In order to optimize the detection technology we have explored, in a recent study, the possible use of a magnetron coil [7] on the inductive volumetric phase shift of the brain in the presence of a edema/haematoma. We have compared the sensitivity of a magnetron coil with that of a circular coil. The results have shown that the magnetron coil has a somewhat greater sensitivity to the detection of a edema/haematoma than the circular coil. This study reveals that the location of the edema/haematoma has a substantial effect on the sensitivity of the magnetron and circular coils. Furthermore, we find that at certain different frequencies the various locations of the edema/haematoma produce no volumetric phase shift.

2. METHOD

2.1. Time-harmonic, Quasi-static Magnetic and Electric Field

In the time-harmonic case, we omit the displacement currents in Ampere’s equation [8]:

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{J} \quad \text{(Maxwell-Ampere’s law)}$$

(1)

where $\vec{H}$ is the magnetic field intensity (A/m), $\vec{D}$ is the electric displacement (C/m$^2$), $\vec{J}$ is the electric current density (A/m$^2$) and $t$ is the time. Using the current density in a conductive medium through the Lorentz force in Eq. (1), we obtain:

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \sigma(\vec{E} + \vec{v} \times \vec{B}) + \vec{J}^c$$

(2)
where $\sigma$ is the medium conductivity (S/m), $\vec{E}$ is the electric field intensity (V/m), $\vec{v}$ is the relative velocity, $\vec{B}$ is the magnetic field density (T), and $\vec{J}^e$ is a current density generated externally. Expressing the magnetic and electric fields in terms of the magnetic vector potential ($\vec{A}$) and the electric scalar potential ($V$):

$$\vec{B} = \nabla \times \vec{A} \quad (3)$$

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t} \quad (4)$$

The complete constitutive equation used for the magnetic and electric fields are:

$$\vec{B} = \mu \left( \vec{H} + \vec{M} \right) \quad (5)$$

$$\vec{D} = \varepsilon \vec{E} + \vec{P} \quad (6)$$

where $\vec{M}$ is the magnetization vector (A/m), $\vec{P}$ is the electric vector polarization (C/m$^2$), $\mu$ is the medium permeability (H/m), and $\varepsilon$ is the medium permittivity (F/m). Using the Eqs. (5) and (6) in Eq. (2) we obtain:

$$\nabla \times \left( \mu^{-1} \vec{B} - \vec{M} \right) - \frac{\partial \left( \varepsilon \vec{E} + \vec{P} \right)}{\partial t} = \sigma \left( \vec{E} + \vec{v} \times \vec{B} \right) + \vec{J}^e \quad (7)$$

Using Eqs. (3) and (4) in Eq. (7):

$$\nabla \times \left( \mu^{-1} \nabla \times \vec{A} - \vec{M} \right) - \frac{\partial \left( \varepsilon \vec{E} + \varepsilon \vec{P} \right)}{\partial t} = \sigma \left( -\nabla V - \frac{\partial \vec{A}}{\partial t} + \vec{v} \times \nabla \times \vec{A} \right) + \vec{J}^e \quad (8)$$

In Eq. (8), we have considered a non-moving geometry ($\vec{v} = 0$) and no external electric potential gradient ($\nabla V = 0$) on the border of the brain sphere, to simplify initial conditions in symmetry boundaries. In addition, we have assumed that the border of the sphere surrounding the system is grounded, then:

$$\sigma \frac{\partial \vec{A}}{\partial t} + \varepsilon \frac{\partial^2 \vec{A}}{\partial t^2} + \nabla \times \left( \mu^{-1} \nabla \times \vec{A} \right) = \vec{J}^e \quad (9)$$

A time-harmonic function using Euler’s formulation can be written as:

$$\vec{A}(\vec{r}, t) = \text{Re} \left[ \vec{A}(\vec{r}) e^{j(\omega t + \phi)} \right] = \text{Re} \left[ \vec{A}(\vec{r}) e^{j\phi} e^{j\omega t} \right] \quad (10)$$

where $\omega$ is the angular frequency, $\phi$ is the phase angle, and $\vec{A}(\vec{r}) e^{j\phi}$ is the phasor. Using this function in Eq. (9) we obtain:

$$(j \omega \sigma - \omega^2 \varepsilon) \vec{A} + \nabla \times \left( \mu^{-1} \nabla \times \vec{A} \right) = \vec{J}^e \quad (11)$$

2.2. Inductive Phase Shift Estimation

Following the proposed spherical model and coil configurations (Fig. 1), consider an alternating current $I e^{j\omega t}$ flowing through the inductor coil, according to Hugo and Burk [9], the presence of a spherical conductive sample (the brain cavity) produces changes in the receiver coil impedance as a function of the electrical properties of the sample ($\sigma$, $\varepsilon$). In this work an arbitrary edema/haematoma represents volumetric changes in those properties.

The impedance of the receiver coil could be characterized by complex voltage $V(\omega)$ and current $I(\omega)$ defined as:

$$Z(\omega) = R(\omega) + jX(\omega) = \frac{V(\omega)}{I(\omega)} \quad (12)$$

where $R(\omega)$ and $X(\omega)$ are the coil resistance and reactance respectively. Thus, the induced receiver coil current could be separated in their complex coefficients [10] given by:

$$I(t) = I(\cos(\omega t + \phi) + j \sin(\omega t + \phi)) \quad (13)$$
where its argument could be obtained by:

\[
\omega t + \phi = \tan^{-1} \frac{\text{Im}(I(t))}{\text{Re}(I(t))} = \tan^{-1} \frac{\sin(\omega t + \phi)}{\cos(\omega t + \phi)}
\] (14)

We define a basal induced current argument in the receiver coil as \((\omega t + \phi)\) and the argument influenced by the edema/haematoma presence as \((\omega t + \phi_1)\). To estimate the inductive phase shift \((\Delta \phi)\) we can use the argument differences at specific frequency and time according to the following expression:

\[
\Delta \phi = (\omega t + \phi_1) - (\omega t + \phi) = \phi_1 - \phi
\] (15)

3. SIMULATION METHOD

We use a commercial software (COMSOL MULTIPHYSICS) [11], which uses the Finite Element Method to solve Eq. (11) for the magnetic vector potential. We simulate the \(\vec{B}\) for every circular/magnetron coil configuration by alternating currents in the inductor coils at the frequencies 0.1, 1, 10 and 50 MHz.

The simulation follows the next geometrical and electrical considerations: the brain cavity model is a sphere of radius 13 cm, the haematoma is a sphere of radius 2.6 cm in arbitrary position inside the brain cavity. The electrical conductivity and permittivity values for brain and blood were considered isotropic and were taken from Gabriel et al. [12]. The circular and magnetron coils were designed by copper electrical properties, thickness 0.4 cm and radii as follows: circular-inductor; inner and external radii of 14 and 14.5 cm respectively, magnetron-inductor; inner and external radii of 14 and 18.6 cm respectively with eight successive slots with radii 1.86 cm, circular-receiver; inner and external radii of 1.4 and 1.45 cm respectively, magnetron-receiver; inner and external radii of 1.9 and 2.5 cm respectively with eight successive slots with radii 0.3 cm.

4. RESULTS AND DISCUSSION

Figure 2 shows the \(\vec{B}\) lines simulated at 1 MHz for the proposed circular/magnetron coil configurations. Spatial distribution differences as a function of the inductor/sensor elements are evident. Circular-receivers (Figs. 2(a) and (b)) shows \(\vec{B}\) irregularly distributed. Magnetron receivers (Figs. 2(c) and (d)) shows high \(\vec{B}\) uniformly distributed. Fig. 3 shows spectra of inductive phase shift in the bandwidth of 100 kHz to 50 MHz. Data are homogenized respect to basal values. The sensitivity increases as a function of frequency and is significantly higher for the magnetron-receiver configurations.

Magnetron coils as elements with high efficient factor produced high magnetic flux densities uniformly distributed in the spherical sample [10], however; spatial distribution differences observed in Fig. 2 correspond to the coil configurations evaluated. Those differences suggest specific mutual inductances associated to the inductor and receiver geometrical properties, is expected that the high magnetic flux density observed for the magnetron-receiver configurations reflect its high inductive phase shift values estimated in Fig. 3. The sensitivity increase as a function of frequency is explained by the effect of water content at high frequencies [13]; where the increase in the conductivity arises from the rotational relaxation of the water dipoles.
5. CONCLUSIONS

The computational simulation shows that measuring the relative spectroscopic distribution of induction phase shift has the potential for being a simple method to produce a robust means for non-contact detection of occurrence of edema/haematoma in the bulk of brain. The circular/magnetron coils evaluated in this study suggest that a system with a magnetron receiver is a feasible configuration for an easy and practical application.

REFERENCES


