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Circular Loop Antenna Operating at 434 MHz for Medical Applications: Loop-Tissue Interaction.

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The interaction between the circular loop antenna and human tissue is investigated. Return loss, radiation efficiency and specific absorption rate (SAR) when in proximity to human tissue is evaluated for various loop orientations with respect to the tissue. The simulated internal SAR distribution is shown for various orientations with respect to the tissue.

Keywords – Loop antenna, specific absorption rate, human tissue.

I INTRODUCTION

Electromagnetic energy at the frequency of 434 MHz has been used for many years in medical applications [1-3]. The loop antenna has been employed to provide non-invasive cancer therapy because it presents low impedance in the near field [4-5], which facilitates the coupling to and penetration into the body.

The loop antenna has been demonstrated to be suitable to achieve efficient power deposition [6] and is used as hyperthermia applicator.

Loop antennas are employed in microwave and RF energy treatments either as single element or in array applicators [7]. In this paper the characteristics of the resonant loop are evaluated and the influence of the human tissue on the antenna radiation characteristics, such as return loss, radiation efficiency, directivity and input impedance are presented.

The most important clinical requirements for an applicator of microwave or RF energy are good coupling to the body and to obtain the required penetration at the operating frequency [8-9].

The penetration of the electromagnetic wave into the body is determined by the skin depth. The skin depth, δ_s , is the distance from the surface of a tissue to where the electric field has decayed to $1/e$ (37%) of its value at the surface.

For a conducting medium, such as the body, the skin depth is given by the equation (1),

$$\delta_s = \frac{1}{\sqrt{\pi f \sigma \mu_0 \mu_r}} \quad (1)$$

where, f is the operating frequency (Hz), σ is the conductivity of the medium (S/m), μ_0 is the magnetic permeability in free space ($4\pi \times 10^{-7}$ H/m) and, μ_r is the relative permeability (dimensionless). The skin depth can be referred too as the depth of penetration.

As can be seen, the penetration depth is dependent on the tissue properties and on the frequency used. This is seen clearly by comparing the penetration depth of a wet tissue (such as muscle tissue) to a dry tissue (such as fat tissue), at the frequency of 434 MHz. Since the human body exhibits no magnetic properties, therefore the relative permeability is $\mu_r = 1$ for all body tissues.

For muscle tissue the conductivity, σ , at 434 MHz is 0.8050 S/m thus the penetration depth, δ_s , is 2.6cm. For fat tissue the conductivity, σ , is 0.0416 S/m thus the penetration depth δ_s is 11.8cm.

Since the work of Yee [10] the time-domain solution of Maxwell's equations has become popular, which instigated the Finite-Difference Time-Domain (FDTD) method [11]. This technique starts with the governing equations in differential form. Another approach was later introduced which starts with the

CST microwave studio and the Finite Integration Technique (FIT) are employed as the numerical solver. The FIT divides the model into different grids and then evaluates those grids using Maxwell's integral equations. The time domain solver was used to calculate the internal field components in the tissue and hence evaluate the Specific Absorption Rate (SAR), as well as antenna resonance, radiation efficiency and input return loss. The loop was excited using a discrete port, placed across the gap. The forward and reflected energy and their respective phases at this port are used to determine the scattering-parameters and hence antenna input characteristics. This solver calculates the development of fields through time at discrete locations and at discrete time samples. It calculates the transmission of energy through the port of the investigated structure. A Discrete Fourier Transform (DFT) is used to calculate frequency domain signals such as the S-parameters from the time signals [13].

The loop antenna was positioned at various orientations, but at a fixed distance from the muscle tissue. The different loop orientations detuned the loop resonance by different amounts and it was necessary to adjust the loop radius to achieve resonance in each case and maximise power deposition into the tissue.

The loop antenna parameters are the loop radius, r , the conductor diameter, D , and the feedgap. In all the models the conductor diameter and feedgap are fixed, but the loop radius is changed for each orientation, in order to achieve resonance [14]. The value of the conductor diameter was $D=3\text{mm}$ and the feedgap was 4mm . The coordinate system and loop geometry is shown in Figure 1.

The antenna was placed at distance of 50 mm from the human tissue which comprised transversal fibre of muscle. The muscle was modelled with the electrical properties given by the Federal Communications Commission (FCC) for the frequency of 434MHz ($\epsilon_r = 56.86$, $\sigma = 0.805\text{S/m}$, $\rho = 1040\text{kg/m}^3$).

The muscle slab modelled has the dimensions 240mm x 240mm and 100mm thick. This homogeneous muscle slab was used in order to see the loop orientation effects on SAR distribution more clearly, as a full body model comprises complex surfaces and internal geometries, which have spatially varying dielectric properties, which would shroud some antenna impedance effects [15]. The different orientations of the loop antenna with respect to the muscle layer are shown in Figure 2.

Figure 2. Different loop orientation.
(a) loop axis z ; (b) loop axis x , with feed opposite to the muscle; (c) loop axis x , with feed close to the muscle; (d) loop axis y .

III ANALYSES OF LOOP IN FREE SPACE

A loop antenna with radius, $r=114.5\text{mm}$, is found to be resonant in free space at the frequency of 434 MHz. The measured and simulated return loss of the antenna in free space against frequency are in good agreement, as shown in Figure 3. At the operating frequency of 434 MHz the return loss in the simulated model is 5.999dB, and the input impedance $(119.1 - 56.71j)\Omega$. The directivity, D , and gain, G , are 3.685dBi and 3.563dB, respectively, and since

$$G = \eta D \quad (2)$$

where η is the radiation efficiency, $\eta = 96.6\%$.

Figure 3. Return loss for the resonant loop antenna in free space.

IV ANALYSES OF LOOP IN PROXIMITY TO HOMOGENEOUS HUMAN TISSUE.

When the same loop antenna (with radius $r=114.5\text{mm}$ and resonant at 434MHz in free space) is placed in proximity to human tissue, variations in the resonant frequency are observed, as is shown in Figure 4. Significant detuning is noticed for some of the loop orientations. The thickness of the muscle slab does not affect to the return loss.

The loop radius is therefore modified for each orientation to provide resonance at 434 MHz, ensuring maximum power deposition into tissue. The conductor diameter and feedgap remains with the same value as the loop in free space.

Figure 4. Loop detuning due to proximity to human tissue, for different loop orientations.

The Specific Absorption Rate (SAR) in the muscle tissue was simulated using CST Microwave Studio. The SAR is defined as the time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given mass density (ρ), as seen in equation (3),

$$SAR = \frac{d}{dt} \left(\frac{dW}{dm} \right) = \frac{d}{dt} \left(\frac{dW}{\rho \cdot dV} \right) \quad (3)$$

The SAR value is expressed in units of watts per kilogram (W/kg). In a tissue, the SAR is proportional to the square of the internal electric field strength as seen in equation (4),

$$SAR = \frac{\sigma_c E^2}{\rho} \quad (4)$$

where, E is the electric field strength at point of exposure (V/m), σ_c is the conductivity of the exposed body tissue (S/m), and ρ is the mass density of the tissue (kg/m^3).

The whole body average SAR is a single value that represents the spatially averaged SAR throughout the body and a limit is placed on this value to prevent the human body from excessive heating by plane-wave exposure [16]. However, in this case where the antenna illuminates only a part of the body, and a local peak SAR value is more useful. The local peak SAR (Spatial peak) is usually averaged over a small volume, typically 10g [17]. However, averaging over a smaller volume is a more precise representation of localised microwave absorption; hence the local peak SAR was averaged over a 1g cuboid volume in this work.

LOOP ORIENTATIONS

a) Z-axis (loop in xy plane)

When the loop is centred on the Z axis, (Figure 2.a) the required loop radius for resonance at 434MHz in proximity to tissue is $r=110.5\text{mm}$. This is 4 mm smaller than the free-space value. The return loss is 12.32dB, and the input impedance is $(78.91 - 12.14j)\Omega$. The directivity and gain are 7.270dBi and 3.108dB respectively, and the efficiency is 42.7%. This low value of efficiency indicates a strong interaction between antenna and tissue.

The SAR distribution for depths of 5, 40 and 95 mm inside the muscle tissue is shown in Figure 5. The SAR values represent local peak values, averaged over 1g, per Watt of power at the loop input port. It can be seen that there are initially two hot spots which converge as the depth increases.

Figure 5. SAR (1g averaged/W) for depths of 5mm, 40mm and 95mm inside the muscle tissue.

b) X-axis (loop in yz plane), with feed opposite to the muscle

When the antenna axis is X (Figure 2.b), the required loop radius for resonance at 434MHz in proximity to tissue is $r=99.5\text{mm}$. The return loss is 9.518dB, and the input impedance is $(97.68 - 13.47j)\Omega$. The directivity and gain are 4.617dBi and 3.734dB respectively, thus the efficiency is 80.8%.

The SAR distribution for depths of 5, 40 and 95 mm inside the muscle tissue is shown in Figure 6.

Figure 6. SAR (1g averaged/W) for depths of 5mm, 40mm and 95mm inside the muscle tissue.

c) X-axis (loop in yz plane), with feed close to the muscle

The required loop radius is $r=99.5\text{mm}$ for this orientation (Figure 2.c). The return loss is 11.78dB, and the input impedance is $(83.27 - 8.794j)\Omega$. The directivity and gain are 4.530dBi and 3.323dB, respectively, thus the efficiency is 73.3%.

The SAR distribution for depths of 5, 40 and 95mm inside the muscle tissue is shown in Figure 7.

Figure 7. SAR (1g averaged/W) for depths of 5mm, 40mm and 95mm inside the muscle tissue.

d) Y-axis (loop in xz plane)

The resonant loop radius for this orientation (Figure 2.d) is $r=95.5\text{mm}$. The return loss is 5.938dB, and the input impedance is $(144.3 - 31.28j)\Omega$. The directivity and gain and efficiency are 3.055dBi and 2.698dB, and 88.3%, respectively.

The SAR distribution for depths of 5, 40 and 95 mm inside the muscle tissue is shown in Figure 8.

Figure 8. SAR (1g averaged/W) for depths of 5mm, 40mm and 95mm inside the muscle tissue.

In Figure 9 is shown the variation of SAR with depth into tissue for the different loop orientations. It can be seen that the SAR is higher when the loop is centred on the Z axis but it falls exponentially with increase in depth inside the muscle.

Figure 9. Plot of SAR (1g averaged/W) against depth for different loop orientations.

V CONCLUSION

Noticeable detuning of the loop antenna in terms of frequency and return loss was observed, depending on the orientation with respect to the tissue slab. The radiation efficiency also varied considerably. The radiation efficiency was found to be least when the loop is placed parallel to the body, indicative of maximum interaction between the loop and the tissue. This orientation provides the best coupling to the tissue and the highest SAR.

Maximum detuning occurred for the y loop axis; the detuning was 88.3%, which considerably reduced the SAR.

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