Specific Absorption Rates in Muscle Tissues for UHF RFID Reader Systems

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Abstract

In this paper, we describe the specific absorption rates (SAR) of radio frequency (RF) energy in muscle tissues for UHF RFID reader systems. Energy dissipation of electric fields are studied for muscle tissues of humans and large vertebrates. An analytical evaluation is conducted for the SAR in muscle tissues for the near-fields and far-fields of the RFID reader. It is shown that the maximum SAR in muscle tissues for a UHF RFID reader is approximately 3.652W/kg, which is more than twice the limit for safe exposure to RF energy produced by mobile devices (1.6W/kg), as adopted by the Federal Communications Commission (FCC).

1. Introduction

In this paper, motivation will be presented for the study of long term effects of RFID systems in a pervasive health environment. RFID systems are slowly dominating the energy spectrum in the healthcare environment, and although are typically low powered systems, must be analyzed and studied analytically. These studies will help us understand the impact of dense modes of passive wireless systems in the future healthcare space. The characterization of RF propagation in muscle tissues is a field that has been extensively studied. However, the results from this field have previously yielded very little insights into the effects of RF energy absorption in biological tissues. The specific energy absorption studied in the past has at times neglected the long term effects of RF energy penetration and often concentrated in high powered signals. In doing so, the magnetic field effects have been largely ignored, while the electric field is often used only to understand the thermal impacts on these biological tissues.

We organize our study as follows: A background of the typical RFID system is presented in Section 2. This section presents the typical UHF RFID reader and antenna system, as well as their propagation models. Section 3 is dedicated to the study of RF fields in muscle tissues for humans and large vertebrates. In this section, the skin effects and SAR is presented for UHF RF exposures. This section is also dedicated to the analysis of the biological effects when related to the RFID reader RF energy propagation model. The general theory of RF propagation and SAR is evaluated in this section for the UHF RFID reader system. Analytical evaluations are also presented in this section to illuminate and visualize the SAR in muscle tissues. We draw the relevant conclusions in Section 4.

2. RFID Reader Antennas and Propagation

The power density of the electromagnetic waves incident on a specific surface area in free space can be modeled using Equation 1, where P_t is the transmitted power, G_t is the gain of the transmitting antenna, and r is the distance from the transmitting antenna to the specified absorbing surface area [1, 2].

$$S = \frac{P_t G_t}{4\pi r^2} \quad , \quad P_a = S A_e \quad , \quad A_e = \frac{\lambda^2}{4\pi} \quad , \quad P_{radiated} = K P_a \quad , \quad K = \frac{4R_a^2}{|Z_a + Z_c|^2} \quad \text{and} \quad P_{radiated} = \frac{P_t G_t \lambda^2}{16\pi^2 r^2} \tag{1}$$

The power absorbed by the given surface area defined by the complex conjugate matched load is also given in Equation 1 [3]. A_e is the effective area of the specified absorption area, where λ is the wavelength of the electromagnetic signal radiated by the RFID reader in free space. The power dissipated by the RFID reader antenna systems' resistance multiplied can be calculated using Equation 1 [3], where K is a factor defining the load impedance mismatch on the amount of radiated power. Assuming for the simplified case when the antenna is loaded with its complex conjugated impedances, $P_{radiated}$ in Equation 1 can be used to calculate the total power radiated. This is the simplified theory of power radiated by the RFID reader antenna. As can be deduced from Equation 1, all parameters are either set by the constraints set by FCC or by the fundamental constraints of passive UHF ISM bands. However, the gain of the RFID reader antenna system is highly dependent on the design used to build the antenna. UHF RFID reader antenna systems typically use a rectangular patch antenna with a metal back plane similar to the depiction in Figure 1 [4].

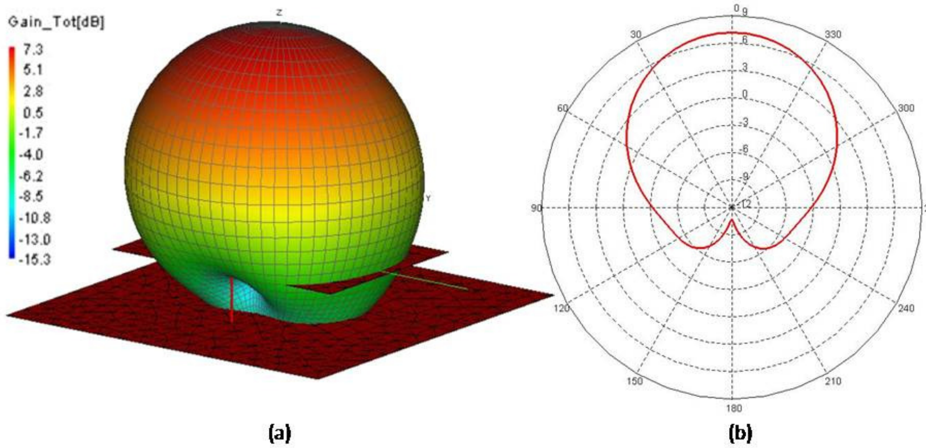

Figure 1: Rectangular patch antenna: (a) 3D gain; (b) 2D gain; in dB for a radiation point source of 1V

The rectangular patch antenna is parametrically described using the width (W), length (L), height (h) and the dielectric constant of the substrate (ε_r). These parameters are described and is calculable using Equation 2 [5], where ϵ_{reff} is the effective dielectric constant and ϵ_r is the dielectric constant. Considering a rectangular patch antenna with air as the dielectric material, it is found that the most efficient values for these parameters using Equation 2 is as denoted in Equation 3.

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \quad , \quad \frac{\Delta L}{h} = 0.412\frac{(\epsilon_r+0.3)}{(\epsilon_r-0.258)}\frac{\left(\frac{W}{h}+0.264\right)}{\left(\frac{W}{h}+0.8\right)} \quad \text{and} \quad L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_o\epsilon_o}} - 2\Delta L \tag{2}$$

$$W = L = 16.3934cm \quad \text{and} \quad h = 4.25cm \tag{3}$$

Using the Equations 2 and 3, an analytical design for the patch antenna is accomplished using numerical techniques developed by computational electromagnetic (CEM) methods. Figure 1b presents the gain of the antenna in dB. We notice that the antenna designed in this section has a maximum gain in the +z-axis of approximately 7.3dB. Similarly, the 3-dimensional gain produced by the UHF RFID reader antenna system is presented in Figure 1a. We notice that the maximum gain observable from this reader system under FCC regulations is at the +z-axis.

In the following section, an overview of the biological effects of electromagnetic fields on human and large vertebrate muscle tissues are presented. The skin effect and SAR are discussed in this section to bring light to the propagation and absorption of RF energy in the muscle tissues.

3. Specific Absorption Rates in Muscle Tissues

Living organisms subjected to a static or non-radiating field will typically extract energy from its source. However, the quantitative descriptions by which this extraction takes place, is very different at higher frequencies [6]. At these higher frequencies, both the electric and magnetic fields of the incoming electromagnetic waves, after reflection at the boundary conditions, are further decreased due to energy dissipation [6]. The magnitude of these fields decrease exponentially with distance from the boundary conditions and is calculable using Equation 4,

$$g(z) = Ae^{-\frac{z}{\delta}} \text{ and } \delta = \frac{1}{\omega\left[\frac{\mu\epsilon}{2}\left(\sqrt{1+p^2}-1\right)\right]^{1/2}} \tag{4}$$

where p is the ratio of conduction current to displacement current in the given media and the skin depth (δ) is defined as the distance at which the field decreases to $1/e = 0.368$ of its value just inside the boundaries [6]. It is widely known that the skin effect becomes much more apparent and significant for humans and larger vertebrates at higher frequencies [6, 7].

Specific Absorption Rates or SAR is the rate at which the body or tissues absorb RF energy when exposed to an electromagnetic field. A dosimetric measure that has been widely adopted is the time derivative of the incremental energy (dW) absorbed by, or dissipated in an incremental mass (dm) contained in a volume element (dV) of a given density (ρ) [6]. Here, σ is defined as the tissue conductivity, and the electric field can be approximated using the Bessel function of the first kind with $n = 0,1,2, \dots, \infty$ as described by Equation 5.

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left[\frac{dW}{\rho(dV)}\right] = \frac{\sigma}{2\rho}|\boldsymbol{E}|^2 = \frac{\omega\epsilon}{2\rho}|\boldsymbol{E}|^2 \quad \text{and} \quad \boldsymbol{E} = g(x,y,z)\sum_{n=0}^{\infty} J_n(x,y,z) \tag{5}$$

Using Equations 1 through 5, we can model the SAR caused by a typical RFID reader system. This theoretical analysis has been shown previously to be accurate [6, 7] and is calculable using Equation 6.

$$SAR = \frac{\omega\epsilon}{2\rho}\left[\frac{P_t G_t \lambda^2}{16\pi^2 r^2}\right]^2 e^{-z^2\omega^2\frac{\mu\epsilon}{2}\left(\sqrt{1+p^2}-1\right)} \sum_{n=0}^{\infty} J_n(z) \tag{6}$$

Extending this equation for the typical UHF RFID system with $P_t = 30dBm$ and $p = 0.59$ for muscle tissues at UHF frequencies (915 MHz), we derive Figure 2, which is the electric field variation and SAR within a sphere of muscle tissue for the reader-tissue separation of 1m, 10m, and 2 reader antenna's at a separation of 20m with the tissue at the origin.

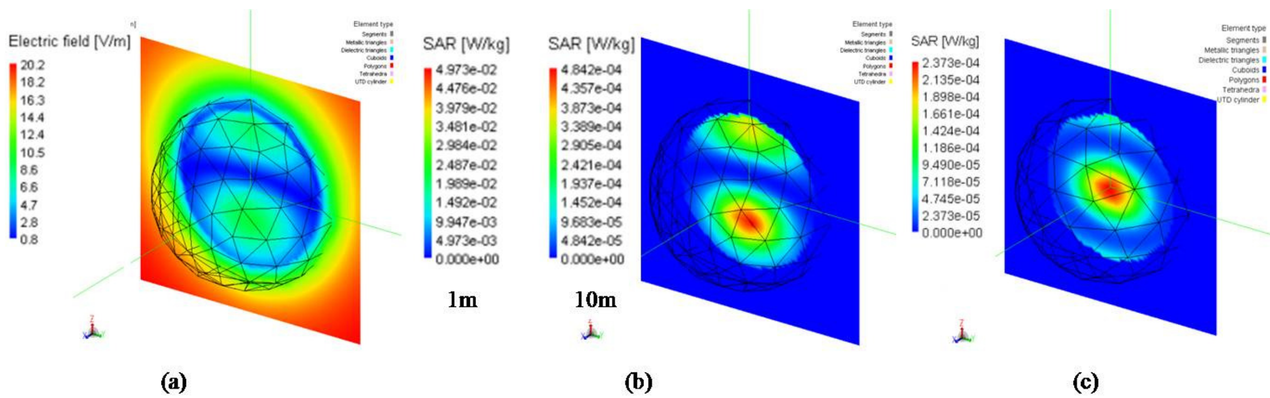

Figure 2: Results for the analysis: (a) electric field at 1m; (b) Maximum SAR at 1m and 10m; (c) Maximum SAR for 2 reader's at 20m apart with muscle tissue at the origin

We notice that the maximum value of the electric field inside the muscle tissue is 20.2 V/m. Figure 2b presents the SAR in the same sphere of muscle tissue for a reader-tissue displacement of 1m. Here it is shown that the maximum value for the SAR in the muscle tissue is 0.04973 W/kg when the RFID reader antenna is 1m away. This is approximately more than 30 times lesser than the 1.6 W/kg limit for safe exposure to RF energy for mobile devices as set by the FCC in the United States [6, 7]. Using similar techniques, we show in Figure 2b also the SAR in the same muscle tissue for a reader-tissue separation of 10m's instead. We notice that the maximum value of SAR of the muscle tissue is 0.0004842 W/kg, when the reader-tissue separation is 10m's. We also notice that the SAR pattern is identical for both cases and that the maximum value of the SAR is almost twice more when the reader is 10m's closer. This is explained by the fact that these field equations are exponential in nature and therefore produce logarithmic features. Although, these results are very important in understanding the nature of the SAR in muscle tissues at near and far-field distances from the RFID reader, the typical pervasive healthcare environment rarely consist of just a single RFID reader system. In needing to describe the environment more closely, an analytical evaluation is conducted with two RFID reader systems facing each other (180°) and at 20m's apart, with the sphere of muscle tissue at the origin. The results of this analytical evaluation produced very low values of SAR in the muscle tissue as depicted in Figure 2c because the electric fields where undergoing tremendous deconstructive interferences with each other. Analyzing a complete model of the human body with 300,000 8mm tetrahedrals using the FEM method and the reader antenna in Figure 1 at 10cm from the front of the human head, we plot the variation of SAR in the volume of muscle tissue within the human head and shoulder's model in Figure 3. Figure 3a depicts the setup used, where Figure 3b shows the muscle tissues and Figure 3c depicts the average SAR at 1.6 W/kg in the human head and shoulders. The analysis conducted shows that for the given volume of muscle tissues within the human head and shoulders, the average SAR is 0.03876 W/kg, the peak 1g cube of tissue SAR is 3.652 W/kg, and the peak 10g cube of tissue SAR is 2.258 W/kg (Table 1).

(a) (b) (c)

Figure 3: Simulation of human body with 25 tissues using FEM with 8mm tetrahedrals and the RFID reader antenna at 10cm for: (a) full simulation test setup; (b) entire human head and shoulders muscle tissue volume; (c) Average SAR at 1.6 W/kg for the setup

Table 1: SAR values and properties for the volume of muscle tissues in the average human body head and shoulders presented in Figure 3

Tissue	Volume m2	Avg. SAR W/kg	Peak 1g Cube SAR	Peak 10g Cube SAR
Muscle	0.00453512	0.03876	3.652	2.258

4. Conclusion

We have presented the generalized theory of SAR in muscle tissues for human and large vertebrates. This theory is used to study the biological effects of electromagnetic wave penetration and to depict the SAR inside and outside a sphere of muscle tissue when the reader is placed 1m and 10m's away from the biological tissue. The SAR is also presented for a two reader environment that is typical of many pervasive healthcare environments today. It is shown that the peak 1g cube value for the SAR of the volume of human muscle tissue in the human head and shoulders with a radiating RFID reader antenna at 1W and 7.3dB gain is $3.652\ W/kg$, which is more than twice the FCC limit ($1.6\ W/kg$) for safe exposure to RF energy by mobile devices.

5. References

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