RESEARCH PAPER

Propagation Characteristics of Electromagnetic Waves in Multilayered Biological Human Tissue

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ABSTRACT:
This paper uses CST-2014 software package and Matlab 2018b to provide the data required to analyze the propagation mode characteristics of the electromagnetic waves (EM) inside multilayered tissue structure such as tissue layer impedance (Z) and tissue layers interface reflection coefficient (K). Moreover, the paper presents the distribution behavior of the electrical field (E-Field) and specific absorption rate (SAR) inside multilayered tissue. The results show that the value of K is of the order of 0.7 at the air-skin interface, but it is about 0.1 at the tissue-tissue interface. The results also reveal that the SAR is directly proportioned to the frequency; in contrast, the standing wave (SW) of the E-filed is inversely proportioned with frequency. Three multilayered phantoms (body-shell, thyroid, and testis) were adopted, and the results were obtained at three resonant frequencies over the ultra-wideband (UWB) frequency span of 3GHz, 6.5GHz, and 10GHz. The simulation results prove the computational formulas.

Key words: Electromagnetic Waves, Multilayered tissue, Human Organ phantom, reflection coefficient and standing wave ratio, specific absorption rate (SAR).
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1. INTRODUCTION:

In recent years, researchers have been interested in analyzing the interaction between the electromagnetic wave present in the atmosphere and human tissue. However, the human tissue is composed of multi-layers with different electrical properties which dependent on radio wave frequency (Mohammed and Saber, 2014). The study of penetration performance of the electric field inside human organs is one of the important topics to be interested in order to estimate the values of the specific absorption rate (SAR). The SAR factor is essential for determining the amount of heat produced in human organs when exposed to electromagnetic waves as well as its importance in many detection and therapeutic applications such as CT scan and Hyperthermia unit (G. and E., 2019).

Besides, it can provide health-monitoring services using body-worn devices (Genovesi, Butterworth and Daniel, 2018). On the other hand, the interactions between electromagnetic radiation and the living organism depend mostly on the quantity and characteristic of the transmitted energy with the kind of the exposed tissue (Adah et al., 2018).

Moreover, some studies show a significant relationship between the amount of electromagnetic waves and the values of Thyroid-Stimulating Hormone (TSH) for people without or with a family history of thyroid dysfunction (Velayutham, Sivan Arul Selvan and Unnikrishnan, 2015; Baby, Koshy and Mathew, 2017). Other researches have demonstrated that continued exposure to high-frequency radiation by communication terminals may cause a decrease in testicle weight and size in mice. Where it
addressed the long term exposure of electromagnetic radiation could causes male infertility in mice. (Mugunthan et al., 2015).

In the literature, considerable numbers of researchers discussed the interaction between the tissue and the electromagnetic waves. (Adah et al., 2018) presented some of the effects of electromagnetic radiation on the male reproductive system. It exhibits that Electromagnetic radiation impacts the male reproductive system causing a reduction in the mobility of spermatozoa, morphometric irregularity, and histological deviations in the testis and occasionally testicular tissue atrophy. Y.E. Mohammed and Ali G. Saber (Mohammed and Saber, 2014), investigated the value of the electrical field with penetration depth into the phantom of the human tissue at different Medical Implant Communication System (MICS) and Industrial Scientific and Medical (ISM) frequency bands. They noted that when the penetration depth ($\delta$) of the muscle greater than its thickness, the reflected signal will form a standing wave ratio. While if the penetration depth ($\delta$) is smaller than its thickness, the exponential fading of the signal will occur inside the muscle.

S. Genovesi, I. Butterworth, and L. Daniel (Genovesi, Butterworth and Daniel, 2018), designed a matching layer (ML) that able to enhance the electric field penetration, they suggested Fat layer to be a ML and they tested for an imping signal with frequency interval (1.0-6.0) GHz. Their results showed that magnitude of the electric field entering the muscle layer is calculated for a fat layer thickness within (1.0-20) mm, also they observed that at lower frequencies (1-1.5 GHz) the penetration is quite good for all the fat layer thicknesses considered.

N. R. Amon, I. Mahbub, and P. K. Saha (Amon, Mahbub and Saha, 2017), studied S-parameters and path loss of the tissue model at frequency range 1-5 GHz to estimate reflected power and received power by tissue. Path loss was found to be around 47-65 dB at 3.1-4.5 frequency band, this frequency range allows high speed rate transmission for in-body and on body communication.

V. Mishra, N. Kumar in (Mishra et al., 2016) suggested a new multilayered human head model that having electrical properties (effective dielectric constant) resemble to real human head to compute E-field, absorbed power density (APD), and SAR.

In this study, the parameters affecting propagation characteristics of the electromagnetic field and specific absorption rate (SAR) were analyzed in multi-layered structure of the body shell, thyroid, and testis phantom layers respectively. These parameters included input impedance of the tissue layer ($Z_{mm}$), complex reflection coefficient between various tissue layer interfaces ($K_{mn}$, the characters $mn$ denote to layer number). Moreover, the distribution of the electrical field (E-field) inside multilayered tissue structure and specific absorption rate (SAR) with corresponding penetration depth ($\delta$) are analyzed in all suggested models. The study is accomplished at three resonant frequencies over UWB frequency span (3 GHz, 6.5GHz, and 10 GHz).

1. Human Organs Modeling

The human tissue exposed to strong electromagnetic radiation from wireless sources faces health hazards. This is due to the fact that most wireless communication devices have sufficient power to establish health hazards. The most susceptible human organs to thermal radiation effect and for the frequencies between 150 MHz and 10000 MHz are body-shell, testis, eyes, and thyroid (Velayutham, Sivan Arul Selvan and Unnikrishnan, 2015; Baby, Koshy and Mathew, 2017; Adah et al., 2018).

In this research, the effect of electromagnetic radiation on the body shell, the thyroid glands, and the testis human organs model is studied. These organs were selected specifically because they are the most parts that are close to the power source at the start of the call, where the mobile device is usually in the pocket and during dialing where the mobile is in proximity to the neck, and in both cases, the wireless terminal transmits high power. The human organs structure is quite complex consist of several tissue layers each one has distinct electrical properties. However, the anatomy of the concerning organs with their respective phantom models are shown in Figure 1.
The human tissue consists of oxygen, hydrogen, nitrogen, and carbon (Klemetsen, 2012), and has frequency-dependent properties. All required electrical properties of human tissue are available in the database of (Hasgall et al., 2015). Table (1) shows some of the electrical properties for the considered tissue and at frequencies of interest.

The body shell, thyroid glands, and testis organ phantom models have been developed with dimensions described in section 4. The models developed to have similar electrical characteristics to that of living organ according to data in the Table 1. However, the multilayered model is adopted in this research to provide a replica of biological organs.

**TABLE 1**

| Tissue type | Conductivity (\(\sigma\)) S/m | Thermal Conductivity W/m\(^{\circ}\)C | Heat Capacity J/kg\(^{\circ}\)C | Density (\(\rho\)) Kg/m\(^{3}\) |
|-------------|-----------------------------|-------------------------------------|-----------------------------|-----------------------------|
| Skin        | 1.74 4.34 8.01              | 0.5                                 | 3662                        | 1125                        |
| Fat         | 0.344 0.971 1.71            | 0.24                                | 2973                        | 961                         |
| Muscle      | 2.14 5.82 10.6             | 0.56                                | 3799                        | 1178                        |
| Thyroid     | 2.44 6.71 12.1            | 0.53                                | 3609                        | 1050                        |
| Epididymis  | 2.65 6.94 12.4            | 0.52                                | 3778                        | 1120                        |
| Testis      | 2.65 6.94 12.4            | 0.52                                | 3778                        | 1120                        |

**Figure 1.** The anatomy of various human organs with their respective phantom models; (a) body shell, (b) Thyroid Gland, (c) Testis.
3. METHOD AND MATERIALS

The essential parameters with their definitions are presented in this section to give good insight about the interaction between microwave signals and biological tissue.

3.1. Dielectric Properties

The dielectric properties of the biological tissue play an important role in distribution of the electromagnetic wave inside biological tissue. The complex dielectric constant of a dielectric medium is given by (Kumar and Kumar, 2014) as:

\[ \varepsilon_r = \varepsilon' - j\varepsilon'' \] (1)

Where \( \varepsilon' \) and \( \varepsilon'' \) are real and imaginary parts of the complex dielectric constant respectively. The relative complex dielectric constant \( \varepsilon_r \) is given as:

\[ \varepsilon_r = \frac{\varepsilon_r}{\varepsilon_0} = \varepsilon'_r - j\varepsilon''_r \] (2)

Where \( \varepsilon'_r \) and \( \varepsilon''_r \) are the real and imaginary parts of the complex relative dielectric constant respectively, and \( \varepsilon_0 \) is the dielectric constant of free space of value \( 8.854 \times 10^{-12} \ F/m \).

The imaginary part of the dielectric constant depends on the medium conductivity \( \sigma \) in S/m and angular frequency \( (\omega = 2\pi f) \) as given by (Kumar and Kumar, 2014) as:

\[ \varepsilon'' = \frac{\sigma}{\omega \varepsilon_0} \] And \[ \varepsilon'' = \frac{\sigma}{\omega \varepsilon_0} \] (3)

Also, the medium loss tangent is given as:

\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega \varepsilon'_r \varepsilon_0} \] (4)

The electromagnetic signals affect the dielectric properties of the tissue through:

1) The electrical conductivity of the tissue, therefore the conduction current with associated energy.

2) The viscosity of the tissue and hence displacement current through the tissue.

Based on database of (Hasgall et al., 2015) and equation 3 the real \( \varepsilon'_r \) and imaginary \( \varepsilon''_r \) parts of the relative complex dielectric constant are calculated for various human tissues, and at three resonant frequencies of interest over UWB span as in Table 2.

| Tissue type | Complex relative Permittivity | \( f_r = 3 \) GHz | \( f_r = 6.5 \) GHz | \( f_r = 10 \) GHz |
|-------------|------------------------------|-------------------|-------------------|-------------------|
| Skin        | \( \varepsilon'_r \)          | 37.5              | 34.5              | 31.3              |
|             | \( \varepsilon''_r \)         | 10.42             | 11.94             | 14.49             |
| Fat         | \( \varepsilon'_r \)          | 10.7              | 9.67              | 8.8               |
|             | \( \varepsilon''_r \)         | 2.05              | 2.64              | 3.06              |
| Muscle      | \( \varepsilon'_r \)          | 52                | 47.5              | 42.8              |
|             | \( \varepsilon''_r \)         | 12.81             | 15.82             | 19.29             |
| Thyroid     | \( \varepsilon'_r \)          | 56.4              | 50.9              | 45.1              |
|             | \( \varepsilon''_r \)         | 14.63             | 18.51             | 21.6              |
| Epididymis  | \( \varepsilon'_r \)          | 56.7              | 51.1              | 45.2              |
|             | \( \varepsilon''_r \)         | 15.88             | 19.17             | 22.27             |
| Testis      | \( \varepsilon'_r \)          | 56.7              | 51.1              | 45.2              |
|             | \( \varepsilon''_r \)         | 15.88             | 19.17             | 22.27             |

TABLE 2
REAL AND IMAGINARY PARTS OF THE COMPLEX DIELECTRIC CONSTANT OF VARIOUS HUMAN TISSUE
The specific absorption rate has been adopted to be a dosimeter quantity of the electromagnetic wave absorbed by the biological tissue and is given by (Stratton, 2007) as:

\[
\text{SAR} = \frac{\sigma E^2}{\rho}
\]  

(5)

Where, \( \sigma \) is the tissue conductivity (S/m) and \( \rho \) is the tissue mass density (kg/m\(^3\)).

Some of the incident electromagnetic fields on the tissue penetrate it, and the penetrated field is decreased with tissue’s depth exponentially, due to energy dissipation according to the following formula (Greenebaum, 2018):

\[
f(z) = F_0 e^{-\delta z}
\]  

(6)

Where \( f(z) \) is the electromagnetic field as a function of tissue’s depth and \( F_0 \) is the amplitude of the electromagnetic field signal just at the tissue boundary. The skin depth (or depth of penetration) \( \delta \) is the depth of the tissue where the field drops to \( 1/e \approx 0.368 \) of its original value of \( F_0 \). For the biological medium and over expansive frequency range \( \delta \) is defined by (Greenebaum, 2018) as:

\[
\delta = \frac{1}{\omega \sqrt{\mu \epsilon_c \left(1 + p^2 - 1\right)}^{1/2}}
\]  

(7)

Where \( \mu \) is the magnetic permeability and for of most biological materials is practically equal to free space permeability \( \mu_0 = 4\pi \times 10^{-7} \) H/m, and \( p \) is the ratio of conduction current on displacement current and for most biological materials is in the range of \( 0.1 < p < 10 \) (Greenebaum, 2018).

The characteristic wave impedance for each tissue layer is obtained by dividing the wave impedance of air (377 ohm) by the square root of the complex dielectric constant \( \epsilon_r \) as in following (Schwan and Li, 1956).

\[
Z_l = \frac{377}{\sqrt{\epsilon_c}}
\]  

(8)

The propagation constant of the radiation \( \gamma = \alpha + j\beta \) is obtained by the equation:

Where \( \alpha \) is attenuation constant, and \( \beta \) is phase constant.

\[
\gamma = \frac{2\pi}{\lambda} \sqrt{\epsilon_c}
\]  

(9)

By assigning single digit subscription \( 1, 2, 3 \) for first, second, third layer respectively, and digit \( 0 \) for the air, and double subscription \( (23, 12, \text{and } 01) \) for the layer interface between third-second, second-first, and first-air layers respectively. The following equations are hold good for the tissue layer characteristic impedance, input impedance,
and complex reflection coefficient \( K = k \ e^{i\phi} \) (Schwan and Li, 1956).

\[
Z_3 = Z_{23} = \frac{377}{\sqrt{\varepsilon_{3r}}} \quad (10)
\]

\[
Z_{12} = Z_2 \frac{1 + K_{23} e^{-2y_2 d_2}}{1 - K_{23} e^{-2y_2 d_2}} \quad (11)
\]

\[
Z_{01} = Z_1 \frac{1 + K_{12} e^{-2y_1 d_1}}{1 - K_{12} e^{-2y_1 d_1}} \quad (12)
\]

\[
K_{23} = \frac{Z_{23} - Z_2}{Z_{23} + Z_2} = \frac{\sqrt{\varepsilon_{2r} - \varepsilon_{3r}}}{\sqrt{\varepsilon_{2r} + \varepsilon_{3r}}} \quad (13)
\]

\[
K_{12} = \frac{Z_{12} - Z_1}{Z_{12} + Z_1} \quad (14)
\]

\[
K_{01} = \frac{Z_{01} - 377}{Z_{01} + 377} \quad (15)
\]

Where \( d \) is the corresponding tissue material thickness.

The tissue interfaces mismatch causes reflection for the incident waves from tissue boundary resulting so-called standing wave, and its strength is given as (Schwan and Li, 1956).

\[
E = E_0 [e^{-\gamma z} + K e^{+\gamma z}] \quad (16)
\]

Where \( z \) is tissue depth coordinate, and \( E_0 \) is the peak magnitude of the field at the input tissue layer (boundary) and determined by the boundary conditions.

The standing wave phenomenon becomes significant in each tissue layer if the thickness of the layer is less than the penetration depth for that tissue layer (Greenebaum, 2018).

4. Simulation Setup and Results

The dipole antenna is simulated using CST-2014 software package to be a source for irradiation the incident electromagnetic wave on the human tissue phantom model. The dipole antenna has been resonated for considered frequencies 3GHz, 6.5 GHz, and 10 GHz. The antenna is situated at distance (50) mm away from tissue phantom model with dimension 75×75 mm², and thickness 5mm,10mm, and 20 mm, these values are empirically selected for the first, second, and third tissue layer respectively as in Figure 3. The reference impedance of the antenna is considered as a 50 Ω. The input discrete port is defined for an antenna with the input voltage and current equal to 1 volt and 1 ampere respectively. The return loss \((RL)\) which is the factor that indicate how well the matching between the transmitter and antenna has taken place. The \( RL \) is given by (GHAFAR, 2005) as:

\[
RL = -20 \log |K| \ dB \quad (17)
\]

Where, \( K \) is the reflection coefficient. For practical applications a return loss of -10 dB is applicable. The return loss response for the suggested antenna at frequencies of interest is shown in Figure 4.

4.1. Reflection Coefficient (K) of Multilayered Tissue Structure

The incident electromagnetic plane wave with linear polarization on the interface between two media will be partially reflected. The equations (13, 14, and 15) describe the computational analysis of the reflection coefficient in biological multilayered media. If the dielectric properties of the two mediums are comparable or in other words if their characteristic
impedances are approximately equal, most of the incident signal is passed to the second medium, and only a little part of the incident wave will be reflected back. In contrast, if there is a considerable difference between their dielectric properties or impedances a little signal will infiltrate to second media, and an almost whole signal is reflected.

Based on the database in (Hasgall et al., 2015) for various electrical properties of tissue, the results obtained from the CST-2014 software for \( \varepsilon' \) and \( \varepsilon'' \), and the equations (10) to (15), a MATLAB code has been written to calculate input impedances \( Z_{01} \), \( Z_{12} \), and \( Z_{23} \), and complex reflection coefficients \( K_{01} \), \( K_{12} \), and \( K_{23} \) between air-skin interface (interface 01) also between subcutaneous tissue layer interfaces (interfaces 12 and 23) of body-shell, thyroid, and testis phantom models and for all frequencies of interest. The results are summarized in Table (3).

Table 3 shows that the value of input impedance between the skin-air boundary and subcutaneous tissue layers boundaries of all models depend on frequency, and accordingly, the reflection coefficients are also frequency-dependent. Moreover, it can be seen from the Table (3) that the magnitude between the input impedance of the air-skin interface (\( Z_{01} \)) increases from 60 to 68 ohms, while the input impedance between tissue-tissue boundaries (\( Z_{12}, Z_{23} \)) ranges around 50 ohms and is close to each other. For this reason, it can be noted that the magnitude of the reflection coefficient of the air-skin interface (\( K_{01} \)) is relatively large (around 0.7) because mismatching with the free space which has a characteristic impedance of 377 ohm, while the magnitude of the reflection coefficient between a tissue-tissue interface (\( K_{12}, K_{23} \)) is less than 0.1 because they have comparable dielectric characteristics consequently closer characteristic impedances. Table (3) also demonstrates that there is a little change in phases for both input impedances and reflection coefficient.

**TABLE 3: INPUT IMPEDANCE AND COMPLEX REFLECTION COEFFICIENT FOR BODY SHELL, THYROID, AND TESTIS PHANTOM MODELS AT 3GHz, 6.5GHz, AND 10GHz RESONANT FREQUENCIES**

| Organ | Frequency | Input impedance | Complex Reflection Coefficient |
|-------|-----------|-----------------|--------------------------------|
| Body-shell Layers (Skin, Muscle, thyroid) | 3GHz | \( Z_{01} \) 51.51, -6.92, \( K_{23} \) 0.3786, -178.3 | \( Z_{12} \) 114.21, -5.42, \( K_{12} \) 0.3087, 3.43 |
|  | 6.5 GHz | \( Z_{01} \) 60.42, -7.76, \( K_{01} \) 0.7260, -177.45 | \( Z_{12} \) 119.06, -7.64, \( K_{12} \) 0.3127, 2.73 |
|  | 10 GHz | \( Z_{01} \) 62.39, -9.54, \( K_{01} \) 0.7196, -176.7 | \( Z_{12} \) 123.5, -9.58, \( K_{12} \) 0.3170, 4.02 |
| Thyroid model (Skin, Muscle, thyroid) | 3GHz | \( Z_{01} \) 49.38, -7.27, \( K_{23} \) 0.0213, -171.6 | \( Z_{12} \) 51.51, -6.91, \( K_{12} \) 0.0800, 174.93 |
|  | 6.5 GHz | \( Z_{01} \) 60.43, -7.72, \( K_{01} \) 0.7260, -177.46 | \( Z_{12} \) 53.28, -9.21, \( K_{12} \) 0.0788, 177.88 |
|  | 10 GHz | \( Z_{01} \) 62.39, -9.54, \( K_{01} \) 0.7196, -176.7 | \( Z_{12} \) 55.02, -12.13, \( K_{12} \) 0.0770, 178.12 |
| Testis | 3GHz | \( Z_{01} \) 49.38, -7.27, \( K_{23} \) 0.0213, -171.6 | \( Z_{12} \) 51.51, -6.91, \( K_{12} \) 0.0800, 174.93 |
|  | 6.5 GHz | \( Z_{01} \) 60.43, -7.72, \( K_{01} \) 0.7260, -177.46 | \( Z_{12} \) 53.28, -9.21, \( K_{12} \) 0.0788, 177.88 |
|  | 10 GHz | \( Z_{01} \) 62.39, -9.54, \( K_{01} \) 0.7196, -176.7 | \( Z_{12} \) 55.02, -12.13, \( K_{12} \) 0.0770, 178.12 |
|  |  | \( Z_{01} \) 64.19, -12.42, \( K_{01} \) 0.7152, -175.68 |
4.2 Electrical field Distribution in Multilayered Human Tissue Structure

The field analysis in multilayered models for the tissue of the human organ is quite difficult than the single layer. In the presence of multilayer (skin layer and subcutaneous layers) each with unique dielectric properties, multiple reflections can occur between these layers. The reflected wave is combined with an incident wave to constitute a standing-wave phenomenon in each layer. The standing-wave becomes significant in the tissue layer if its thickness is less than its penetration depth (Greenebaum, 2018).

The equation of the electrical field distribution in biological tissue was given by equation (16).

Figure 5 show the CST simulated results of the induced electric field distribution along the phantom depth coordinates (z) in the multilayered structure of body-shell, thyroid, and testis phantom models respectively.
Figure (5) reveals a set of important points as a follow:

1. The strength of the induced electrical field in the skin layer and all subcutaneous layers depends on the frequency, and for all proposed models. Where the electric field strength (E-Field) at the boundary surface of the air-skin layer, and at the frequencies 3GHz, 6.5GHz, and 10 GHz are 31.1 V/m, 15.8 V/m, and 6.8 V/m respectively for the body-shell phantom, and 21.6 V/m, 13.1 V/m, and 5.7 V/m respectively for thyroid phantom, also for the testis phantom are equal to 15.2 V/m, 6.8 V/m, and 5.8 V/m respectively.

2. The strength of the electric field decreases as the signal penetrates more distance in tissue layer.

3. The phenomenon of standing-wave more significant in low frequencies than high frequencies (i.e., in the case of 3 GHz higher than 6.5 GHz which is in turn higher than 10 GHz) as stated in (Greenebaum, 2018), where the peak values of the standing wave signal in first layer (skin layer) at 3GHz, 6.5GHz, and 10 GHz frequencies are 57.4 V/m, 37.1 V/m, and 25.2 V/m, respectively, in the body-shell phantom, and 39 V/m, 29.5 V/m, and 20.2 V/m, respectively, in thyroid phantom model, also, in the testis phantom are equal to 37.4 V/m, 27.6 V/m, and 20.4 V/m, respectively.

4. The value of the standing-wave phenomenon in first layer (skin layer) of the phantom models is greater than the second layer (either Fat, Muscle, or Epididymis), and second layer in turn greater than third layer (either Muscle, thyroid, or testis), and this because the thickness of the first layer is less than the second layer which in turn less than the third layer as compared with skin depth.

4.3. Specific Absorption Rate in Phantom Models

The energy of the electromagnetic (EM) waves that strike the human tissue is absorbed by the tissue. The specific absorption rate (SAR) factor measures the rate of absorption of the EM waves in biological tissue as described in equation (5). The absorbed energy undergoes a successive reduction in its magnitude as it launches in the tissue layer as declared in the equation (7).

Figure 6 shows the simulated specific absorption rate in body-shell, thyroid, and testis model versus tissue depth coordinate (z) and for the 3GHz, 6.5GHz, and 10GHz respectively.
Figure 6 demonstrates decreasing SAR value versus penetration depth. Moreover, the SAR depends on the frequency of the EM signal.

The important point to be noted from Figure (6) is how skin-depth ($\delta$) decreases with increasing frequency for all tissue models, where it is seen at
the distance 0 mm (skin boundary) the SAR value is high for higher frequencies, which is at the frequencies 3 GHz, 6.5 GHz, and 10 GHz equal to 0.84 W/kg, 1.27 W/kg, and 1.36 W/kg respectively for the body shell phantom, and based on 1g measure standard. These values are equal to 1.02 W/kg, 1.37W/kg, and 1.43 W/kg respectively, for thyroid phantom. Similarly, for the testis phantom these values are somewhat larger than their peers in other phantoms, which are equal to 1.09 W/kg, 1.39W/kg, and 1.45 W/kg respectively. The SAR values are sharply going down after penetrating a little distance in the tissue layer for higher frequencies. This proves the equation (7) that shows the inversely proportional relationship between skin-depth and frequency. Figure 6 also shows that the skin depth ($\delta$) (the depth of tissue at which the SAR value drops to 0.368 of its value at the boundary (i.e., at tissue depth=0mm) as described in section 3.2) at the three resonant frequencies 3GHz, 6.5 GHz, and 10 GHz are 23mm, 12mm, and 7mm respectively for the body-shell phantom. For the thyroid phantom and at the corresponding frequencies are equal to 21mm, 13mm, and 11mm respectively. Regarding the testis phantom, these values are comparable to those in thyroid phantom, which are 19mm, 13mm, and 11mm respectively.

5. CONCLUSIONS
The investigation involves the study of tissue medium characteristics (input impedance $Z$ and reflection coefficient $K$), the electrical field (E-field), and specific absorption rate (SAR) inside multilayered tissue phantom. Several important points are included in this study. Firstly, the input impedance of the first layer boundary (air-skin) is about 60-68 ohms with corresponding reflection coefficient $K$ is relatively large (about 0.7). While the input impedance for subcutaneous layers boundary (tissue-tissue) is around 50 ohms with a corresponding reflection coefficient around 0.1. Secondly, the electrical field (E-field) and the SAR absorbed by tissue depend on the incident wave frequency, which there is a direct relationship between them. Thirdly, the penetration depth ($\delta$) is inversely proportioned with the frequency of EM waves. Lastly, the standing wave phenomenon due to tissue layers boundary interface is inversely proportioned with the absorbed wave frequency, where the standing wave becomes more significant when the penetration depth greater than the thickness of the tissue layer. Therefore, the standing wave in the skin layer is greater than in the subcutaneous layers because its thickness is less than the subcutaneous layer thicknesses.

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