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Calculation of the Average Specific Absorption Rate of the Human Body Based on the Cylindrical Antenna Model

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Abstract

The international recommendations and standards for the radiofrequency (RF) dosimetry of the human body use the body-averaged specific absorption coefficient (WBA-SAR) as an approximate indicator for measurement of increase of the body temperature. We propose the analytical-numerical approach to analyze the RF dosimetry of the human grounded body. The body being in a far zone is irradiated by the plane EM field; the considered frequency range is 1 - 200 MHz; the approach is based on a cylindrical antenna model. The human body is represented by a homogeneous cylindrical monopole antenna with losses. The model allows studying the influence of body mass, human height and dielectric properties of body components on the WBA-SAR values.

Keywords

Radiofrequency Dosimetry, Cylindrical Antenna, Equivalent Model, Specific Absorption Rate (SAR), Body-Averaged SAR (WBA-SAR)

1. Introduction

The growing use of electromagnetic (EM) fields for a variety of applications in everyday life is one of the technological breakthroughs of our time. However, public concern about the possible negative effects of EM fields increases. Continuous exposure to radiofrequency (RF) EM fields throughout the body leads to an increase in the internal temperature of the human body. A series of international standards [1] and recommendations [2] that use WBA-SAR as an approximation for quantifying body temperature rise have been developed to address this issue. The WBA-SAR is the quantity of RF power absorbed by the human body and averaged over body mass. Since WBA-SAR cannot be measured inside the human body, the computational data are applied to correlate WBA-SAR with experimental measurements; the incident electric field is used mainly for this goal.

Previous RF dosimetry studies have used simple human body models based on common geometric shapes to enable analytical solutions or simple numerical methods [3] [4]. Now, the usual approach to calculate WBA-SAR is to apply the finite difference time domain (FDTD) method based on real voxel-based high-resolution human body models [5]-[7]. Based on recent studies of body dosimetry of RF radiation, an analogy has been found between the human body and a quarter-wave monopole antenna. However, little progress has been made in analyzing the calculation results from the perspective of antenna theory. The similarity between a quarter-wave monopole antenna and a grounded human body was described in [8]-[10]; this was based on statistical analysis of FDTD calculation results using voxel-based models of the human body. The above results have been obtained in a series of papers focusing on the antenna theory. In addition, other previous studies used the theory of cylindrical antenna to calculate the induced current inside the human body if it is irradiated by the EM fields. The model of cylindrical antenna for the human body, based on a semi-analytical approach, was applied to analysis of the impact of the power line EM fields [11]. In [12], authors used the Method of Moments (MoM) for calculation of the induced current in the human body in the framework of thick-wire model. The proposed approaches gave quite accurate results, which are comparable with the FDTD algorithm results that are based on the human body voxel model [13].

The binomial approximation method was used in [14] at the frequency range of 50 - 200 MHz. The approach in framework of the cylindrical dipole antenna model allows calculating the induced current of an isolated or ungrounded human body. The results have been applied to determinate the current magnitude induced inside the body of radio operators. In this context, we deal with an approximate approach, which is based on the three-term approximation method [11] for the analysis of WBA-SAR, in which a grounded human body is considered as the equivalent cylindrical monopole antenna. The monopole cylindrical antenna approximates a ground standing human body; at the same time, the dipole cylindrical antenna corresponds to a human body without load.

The grounded human body in our approach is approximated with equivalent monopole cylindrical antenna related to infinite conducting plane [15]. The simple geometric shapes, likely the cylinder, elongated spheroid, or cuboid, were used to approximate the human body in early studies [3] [4]. In contrast to the previous studies, we do not use the cylinder for approximation of the physical parameters of the human body; but we determine the parameters of a cylindrical monopole antenna, which allows getting the equivalent values of WBA-SAR compared to the FDTD results for real voxel-based models of human body. The proposed approach allows to determine how the different parameters of human body influence on the WBA-SAR values.

The analysis is aimed to study of the influence of human body parameters such as weight, height, and dielectric properties of the body tissues, with additional investigation of the influence of footwear (dielectric layer). This approach can be applied for the frequency range below 200 MHz. This frequency range is important in the RF dosimetry of human body, because the resonant frequency of both grounded and isolated human bodies are included into the above range. The frequencies, at which the maximum WBA-SAR value appears, are defined as the resonant frequency in the RF dosimetry. A similar approach has been applied for the analysis of WBA-SAR for the isolated or ungrounded human body [15], for studying the influence of the antenna model of human body on the human body communication (HBC) [16], as well as for determining the correctness of the human body antenna model [17]. In addition, the engineering design of the equivalent human body antenna representation has been shown to be accurate for measuring the current at the base of the body [18].

An expression for the total axial induced current and WBA-SAR of an equivalent monopole cylindrical antenna are obtained, which are based on a three-term method [19]. In the following, the calculating parameters of the equivalent cylindrical antenna are related to the real physical properties of human body. For the goal to reduce the applicability of the approach, an explicit formula for resonant frequency is given, following [17]; and it is validated by comparison of the maximum values of induced axial current in the antenna. Finally, we investigate the impact of height, weight, and dielectric properties of the body on the WBA-SAR values. More attention is paid to the determination of WBA-SAR by analyzing the effect of shoe lining on WBA-SAR and refining the resonant frequency.

2. Cylindrical Antenna Model

2.1. The Total Axial Induced Current

We will assume that a grounded standing human body at its irradiation by harmonic vertically polarized plane wave can be presented by equivalent cylindrical monopole antenna, in which a rotationally symmetric current density is induced [15]. An approximate analytical formula for this axial current inside in such antenna with the height h, the radius a, and the complex conductance σ_ω^* is based on the three-term approximation [11] of the axial current in a loaded receiving and non-ideally conducting cylindrical antenna and according to [16] [19] and [20] has the form

$$I_z(z) = U_0 u(z) + V_0^e v(z), \tag{1}$$

where U_0 and V_0^e are given as

$$U_0 = E_0/k_2, \quad V_0^e = -2I_{sc}(0) Z_A Z_L / (2Z_A + Z_L), \tag{2}$$

and

$$u(z) = (4i\pi/\zeta_0)\left[H_U(\cos\gamma z - \cos\gamma h) + H_D(\cos(k_2 z/2) - \cos(k_2 h/2))\right], \quad (3)$$

$$v(z) = \frac{2ik_2}{\gamma\zeta_0\Phi_{dR}\cos(\gamma h)}\left[\sin\gamma(h - |z|) + T_U(\cos\gamma z - \cos\gamma h) + T_D(\cos(k_2 z/2) - \cos(k_2 h/2))\right], \quad (4)$$

$E_0\left(\mathrm{V}\cdot\mathrm{m}^{-1}\right)$ is the intensity of the electric incident field on the surface of cylinder (in volts/meter); k_2 is wavenumber of free space; $Z_A = 1/(2v(0))$ (in ohm Ω) is the impedance of the fixed point of the cylinder when it is active; Z_L (in ohm Ω) is load resistance at the base of the cylinder; $I_{sc}(0) = U_0 u(0)$ is current at the ground without load; and ζ_0 is impedance of a free space.

The formulas for the coefficients $\Phi_{dR}, T_U, T_D, H_U, H_D$, which are frequency-dependent, in formulas (3) and (4) are given in [16], they represent integrals that are determined numerically. Following to [19], the non-ideal conducting nature of an equivalent cylindrical antenna is described in terms of complex propagation constant γ, which is

$$\gamma = k_2\sqrt{1 - 4i\pi z^i/(k_2\zeta_0\Phi_{dR})}, \quad (5)$$

where the value $z^i\left(\Omega\cdot\mathrm{m}^{-1}\right)$ (ohm/m) is surface resistance related to the unit length of cylinder with radius a; and according to [19] is defined by relation

$$z^i = \frac{\kappa}{2\pi a\sigma_\omega^*}\left(J_0(ka)/J_1(ka)\right) = r^i + ix^i, \quad (6)$$

and functions J_0 and J_1 are Bessel functions of the zeroth and first order, respectively. The parameter κ is calculated in form

$$\kappa = \sqrt{-i\omega\varepsilon_0\mu_0\left(\sigma_\omega^*/\varepsilon_0 - i\omega - 4\pi z^i/(\mu_0\Phi_{dR})\right)}, \quad (7)$$

where ε_0 is the dielectric permittivity of the free space, μ_0 is the magnetic permeability of the free space, and parameter ω corresponds to the angular frequency.

2.2. The Total Dissipated Power in the Cylinder

The value P_{diss} of total average dissipated power in the cylinder according to [21] is determined by formula

$$P_{diss} \simeq (1/2)\int_0^h r^i\left|I_z(z)\right|^2 \mathrm{d}z, \quad (8)$$

and $r^i = \mathrm{Re}(z^i)$ (see (6)). The WBA-SAR value is determined as the averaged total RF power, which is absorbed by the human body related by the total mass of body [5]. Thereby, for a uniform cylinder with height h, radius a, density ρ and weight $W_c = \rho\pi a^2 h$, the total average power SAR_{cyl} per unit mass, which is absorbed, is given by

$$SAR_{cyl} = P_{diss}/W_c = \frac{r^i}{2\pi\rho a^2 h}\int_0^h\left|I_z(z)\right|^2 \mathrm{d}z, \quad (9)$$

2.3. The Parameters of the Cylindrical Equivalent Antenna Model

The parameters of the cylindrical equivalent antenna model were determined based on the anatomical values of the human body [8]. These parameters are its radius a (m), density ρ (kg·m^{-3}), height h (m), and complex conductivity σ_ω^* (Sm^{-1}) of the material from which the cylinder consists of. In addition, the anatomical parameters of the human body used are weight W(kg), height H(m), average density ρ_m (kg·m^{-3}) and complex conductivity of muscles σ_{mus}^* (Sm^{-1}). Muscle tissue density was chosen because it is one of the main tissues in the body; and also because muscle tissue is widely used in homogeneous models of the human body.

Taking into account the similar considerations regarding the equivalent cylindrical antenna model of the isolated human body [15], the size/weight parameters are determined by formulas

$$a = C_1\sqrt{W/(\pi\rho_m H)}, \quad h = H, \quad \rho = C_2(\rho_m/x), \tag{10}$$

and the conductivity is

$$\sigma_\omega^* = C_3\frac{2g}{3-g}\sigma_{mus}^*, \tag{11}$$

C_1, C_2 and C_3 are proportionality constants; the conductivity σ_{mus}^* is determined by the Cole-Cole dispersion [22]; density $\rho_m \approx 1050\ \mathrm{kg\cdot m^{-3}}$ (see [23]); g is a specific human body function (see [15]). The function g for men and women is determined by relations

$$g = 0.321 + (33.92H - 29.53)/W, \tag{12}$$

$$g = 0.295 + (41.81H - 43.29)/W. \tag{13}$$

The formulas (12) and (13) demonstrate that the specific function g is determined by the person's weight and height. So, one can see that g is connected with the person's fat-to-muscle ratio [24], which results in the WBA-SAR values.

At the given frequency, and physical parameters of person, formula (9) for SAR_{cyl} can be considered as a function of three unknowns parameters C_1, C_2 and C_3. The value of these parameters can be approximated by computations of the values of SAR_{cyl} calculated by the FDTD method for known voxel models corresponding to man, women, and child. For the frequencies in range from 1 MHz up to 200 MHz, the value $Z_L = 0$. The series of such calculations was performed in [5] and [24]. It was found that the values of the parameters C_1, C_2 and C_3 depend on the anthropological parameters of human body [24]. Therefore, the corrected anthropological parameters a, ρ, and σ_ω^*, which are supported by the values C_1, C_2, C_3, and g are one of warranties, which allows to affirm the adequacy of the improved linear antenna model and its essential difference from a conventional linear antenna.

2.4. Determination of the Resonant Frequencies

The knowledge about the range of frequencies at which the SAR values attain the maximum is very important in order to decrease the impact of the RF radiation on the human body. We confine ourselves with the case when the load impedance Z_L in the formula (1) for current is equal to zero. Then the total axial current is

$$I_z(z) = U_0 u(z). \tag{14}$$

If to replace the value (14) in the formula (9) for SAR, one can find its maximal value with respect to frequency if to differentiate (14) with respect to propagation constant γ, which is defined by formula (5). One can found that the relation

$$\gamma h = k_2 h \sqrt{1 - \left| \frac{4\pi i z^i}{k_2 \zeta_0 \Psi_{dR}} \right|} \simeq 1 \tag{15}$$

is condition of maximum. The second term (its imaginary part) in the square root is negligible because the value $k_2 h$ is real. This allows to approximate the second term in the square root by its amplitude. If to replace z^i by (6) and to consider the quadrate of (15), we get

$$k_2^2 - \left| \frac{2i}{\zeta_0 \Psi_{dR}} \frac{\kappa}{\sigma_\omega^*} \frac{J_0(\kappa a)}{J_1(\kappa a)} \right| \frac{k_2}{a} - \frac{1}{h^2} \simeq 0. \tag{16}$$

One can check that for the considered values of radius a and complex conductivity σ_ω^* of the used human body model, the value in the last formula tends to 0.12 in the studied frequency range. The frequency dependent parameters in the module of (16) are functions of the complex conductivity of human body parts, the main percentage of ones is muscle, and its complex conductivity has constant magnitude in the frequency range to be considered. Additionally, the values of Bessel functions change slightly for the values of a, which is characteristic for our model. Therefore, we can replace the term in the module with its approximate value 0.12. If to use known relations $k_2 = \omega\sqrt{\varepsilon_0 \mu_0} = \omega/c = 2\pi f_{res}/c$, and to replace the radius a with that defines the weight W ($W = \rho\pi a^2 h$) of human, we get from (16)

$$f_{res} \simeq \frac{c}{4\pi}\left[1.742\left(\frac{\pi h}{W}\right)^{1/2} + \left(3.0345\frac{\pi h}{W} + \frac{4}{h^2}\right)^{1/2}\right], \tag{17}$$

and c corresponds to the light's speed.

The last formula has a great importance, because it can determine the value of the resonant frequencies, which correspond to the certain physical parameters of human body, and to determine the maximal values of SAR that can be got each individual.

3. Numerical Simulation Results

3.1. Study of Current Distribution Characteristics in an Antenna

Let us consider the behavior of currents induced on the antenna when a plane wave with amplitude $E^{inc} = 1\ \text{V/m}$ is incident on it. The environment and parameters of the human body are characterized by the following quantities: $\varepsilon_0 = 8.854 \times 10^{-12}\ \Phi/\text{m}$ is dielectric constant of free space, $\mu_0 = 1.257 \times 10^{-6}\ \text{H/m}$

is magnetic permeability of free space, $\sigma = 11.5[\text{S/m}]$ is average conductivity of the human body, $\varepsilon_r = 35.0$ is relative average dielectric constant of the human body, $Z_L = 0$ is resistance of the body base load, $\zeta_0 = 120\pi[\Omega]$ (ohm) is impedance of free space. The frequency values vary in the range from 1 MHz to 200 MHz.

Figure 1 shows the value of the current amplitude at the point $z = h/2$, where h is the height of the antenna that models the human body in a standing position. The values are given for three different heights in the frequency range under consideration. As follows from the physical properties of the linear antenna, the maximum current amplitude is observed for an antenna with a height of $h = 2.0$ m. It is also characteristic that the current maximum is shifted to the higher frequency region for antennas of shorter length. The adequacy of the obtained results can be confirmed by calculations of resonant frequencies [25].

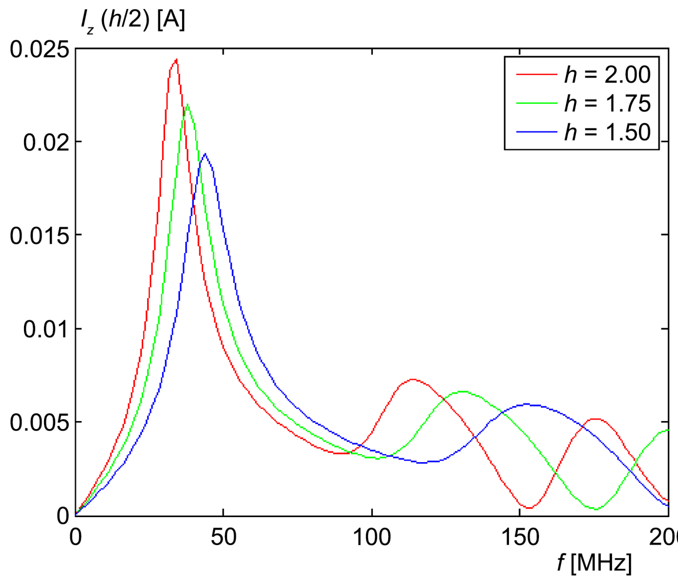

Figure 1. The maxima of current's amplitude for the different hight of antenna.

The general characteristic of the current distribution on the antenna for several frequencies is shown in **Figure 2**. The data are shown for frequencies from 50 MHz to 200 MHz with a step of 37.5 MHz. As can be seen from the figure, the current values are not speedy oscillating functions for a given frequency range that is important at the numerical integration in the process of determining WBA-SAR (formula (9)).

The significant influence on the current's values has the thickness of the gap (rubber sole) between the antenna (human body) and ground base. The results in **Figure 3** are related to high $h = 2.0$ m and show the dependence of current $I_z(z)$ in the middle $z = h/2$ of antenna at the different values t of rubber substrate with $\varepsilon_r = 3.5$. One can see that the height of substrate influences on the value of $I_z(h/2)$ considerably. For example, the value of $I_z(h/2)$ at $t = 6$ cm is almost twice as much as at $t = 0$ cm. This does not contradict the physics of antenna practice and testify that the increase of substrate results in the concentration of energy in the human body, which result in the increment of the SAR values. Note that the green curves in **Figure 1** and **Figure 3** coincide.

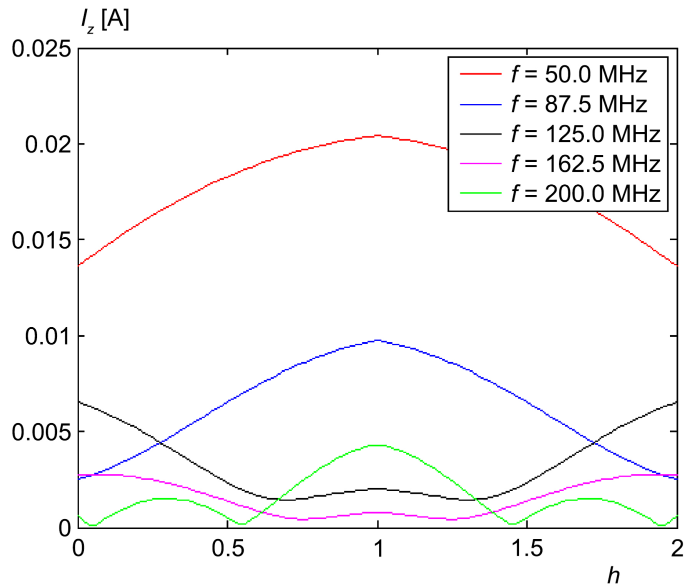

Figure 2. The distribution of the current's amplitude.

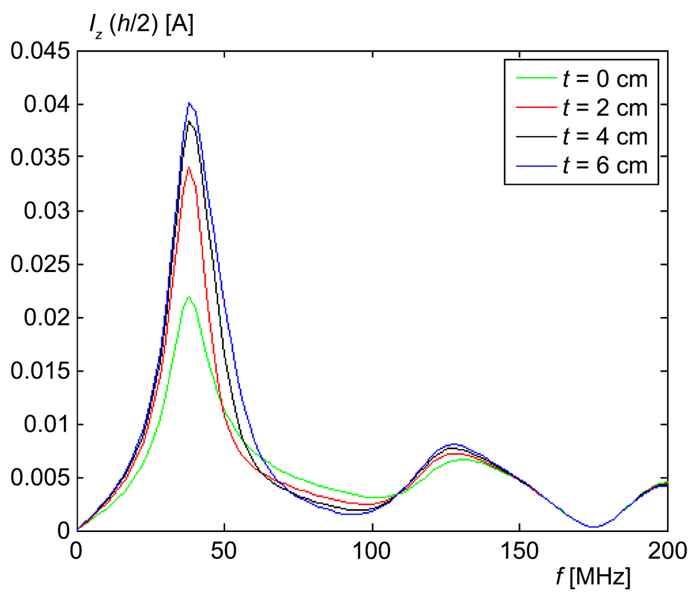

Figure 3. The values of $I_z(h/2)$ versus the thickness of the rubber substrate.

3.2. The Impact of Height and Weight on the SAR Values

The semi-analytical approach used here to analyze the equivalent cylindrical antenna and calculate the total axial current has been proven to be accurate in the analysis of the cylindrical antenna, provided that the conditions $k_2 a \ll 1$ and $h \gg a$ are satisfied. For the equivalent cylindrical antennas under investigation, the condition can be satisfied for the frequency range below 200 MHz, which is an important frequency range in radio frequency dosimetry of the human body, since it contains resonant frequencies.

In **Figure 4**, the results of WBA-SAR determination for a given frequency range at the average body conductivity $\sigma = 12.0$ and relative permittivity $\varepsilon_r = 35.0$ [22] are shown. The average density of the human body is given as $\rho = 1050$ кг/м$^{-3}$. The results demonstrate the characteristics of WBA-SAR are similar to that the distribution of currents $I_z(z)$ because the first are determined as the squares of $I_z(z)$ amplitudes, and the points of the WBA-SAR maxima corresponds to the pints of the $I_z(z)$ maxima.

The obtained results demonstrate a nonlinear dependence of WBA-SAR on frequency, and the maximum value achieved is equal to 1.72 μW/kg, 1.25 μW/kg and 0.85 μW/kg for heights $h = 2.00$ m, $h = 1.75$ m and $h = 1.5$ m, respectively, which does not contradict the nature of EM absorption.

Calculations were made for the case of an increase in the mass fraction of adipose tissue, which leads to a decrease in density. Numerical results for $\rho = 900$ kg/m^3 at $h = 2.00$ m show that in this case the WBA-SAR value is equal to 1.70 μW/kg, *i.e.* it does not decrease much relative to the change in weight (14% change in weight and only 1% change in WBA-SAR).

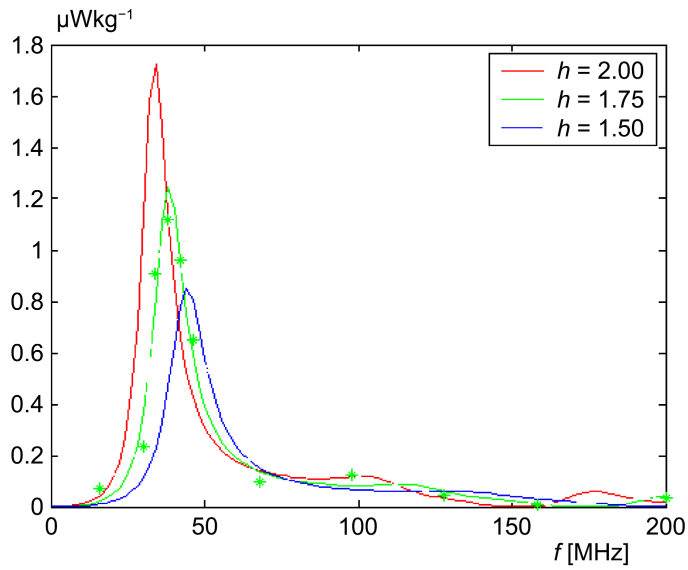

Figure 4. The WBA-SAR values at the different hieghts of antenna.

In **Figure 5**, the respective WBA-SAR values are shown for the case, when the rubber substrate is taking into account, and $\varepsilon_r = 3.5$. The results are presented for $t = 0.0$ cm, $t = 2.0$ cm, $t = 4.0$ cm, and $t = 6.0$ cm at $h = 1.75$ m. Similarly to characteristics of $I_z(z)$, the value of WBA-SAR increases if the thickness of substrate grows. But this increase is more visible than in the case of current.

The value of WBA-SAR are equal to 4.26 μW·kg^{-1}, 3.92 μW·kg^{-1}, 3.10 μW·kg^{-1}, and 1.25 μW·kg^{-1} for $t = 6.0$ cm, $t = 4.0$ cm, $t = 2.0$ cm, and $t = 0.0$ cm, respectively.

Despite the fact that the behavior of $I_z(z)$ and WBA-SAR are similar, the growth of WBA-SAR is much greater than growth of $I_z(z)$: about 3.4 times for WBA-SAR in contrast to about 1.9 times for $I_z(z)$.

In order to validate the values of calculated WBA-SAR, the comparison with that were obtained by the FDTD approach in papers [5] and [24], was carried out. The results were extracted for height $h = 1.75$ m. The FDTD data are marked by stars. As one can see, both the data are coincided well. So, the difference between our results and those obtained in the mentioned papers does not exceed 12% in the vicinity of the resonant frequencies, and it does not exceed 17% for other frequencies beyond. Such difference is characteristic for the case of the case of ideal conducting support (**Figure 4**) and for the case with the rubber substrate (**Figure 5**); the data are shown for the height $t = 2.0$ cm of rubber substrate; the values corresponding to FDTD calculations are marked by stats. The comparison for the case of higher frequencies can not be done because of the lack of data for the studied frequency range.

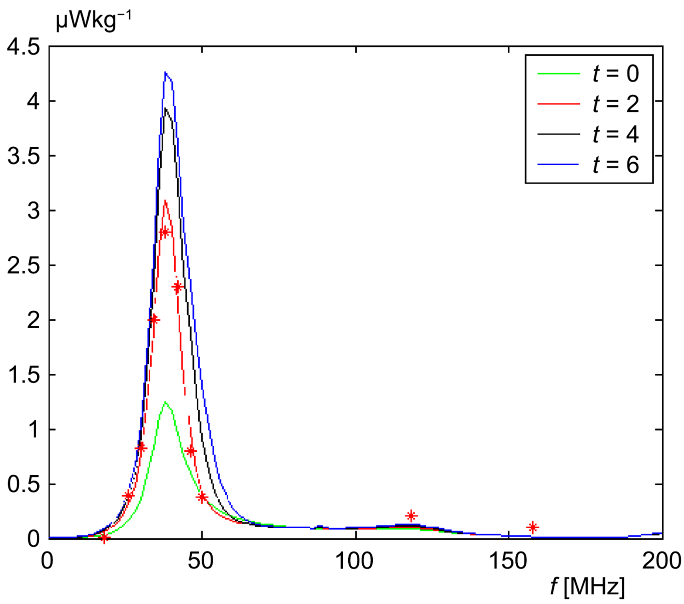

Figure 5. The values of WBA-SAR versus the thickness of the rubber substrate.

3.3. Influence of Dielectric Properties of Tissues

In order to investigate the dependence of WBA-SAR on the dielectric properties of the body, numerical calculations were performed with different values of conductivity. The results are shown in **Figure 6** for values σ that are increased and decreased by half compared to the value in **Figure 4** at $h = 1.75$ m.

As the conductivity σ decreases, the value of WBA-SAR increases, since most of the energy is absorbed by the human body. Thus, for the maximum WBA-SAR values for the $f = 38$ MHz frequency, these values are 5.24 μW/kg, 3.80 μW/kg and 3.69 μW/kg for the $\sigma = 6.0$ [S/m], $\sigma = 12.0$ [S/m], and $\sigma = 18.0$ [S/m], respectively.

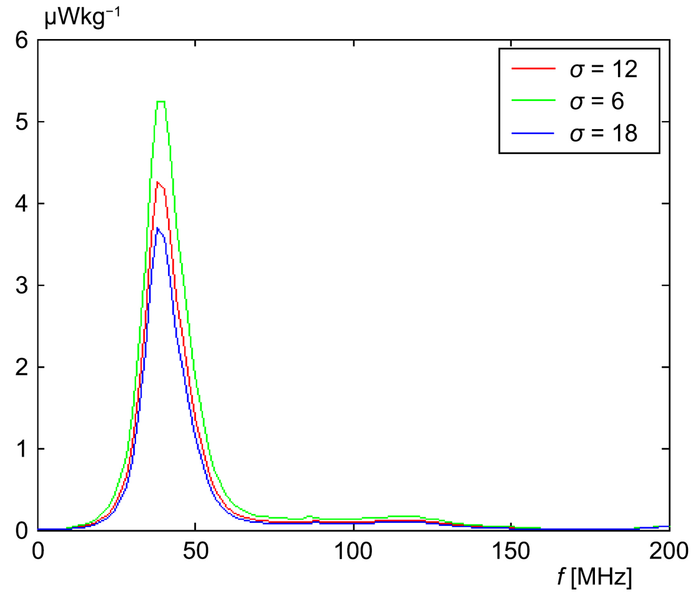

Figure 6. The values of WBA-SAR versus the conductivity σ.

The relation between the height of human body and maxima of the attained SAR changes considerably when to move to the higher frequencies. The values of attained maxima of SAR in the frequency range from 200 MHz up to 400 MHz are shown in **Figure 7**. One can see that the maxima move considerably when height h changes. The maxima appear at 248 MHz, 280 MHz, and 324 MHz for the heights $h = 2.0$ m, $h = 1.75$ m, and $h = 1.5$ m, respectively; and maxima are 1.35 μW·kg^{-1}, 1.79 μW·kg^{-1}, and 6.20 μW·kg^{-1}. Such features of SAR are explained by the different influence of EM radiation on the human body than in the range of lower frequencies. The above testifies that in the range of higher frequencies the impact of EM radiation is more significant.

The calculations in the range of higher frequencies demonstrate that the properties of the WBA-SAR differs much on that are characteristics for the lower frequencies. The data of modeling show that in the range of frequencies from 800 MHz up to 1200 MHz the values of WBA-SAR are characterized by the low level do not exceed dozens of W·kg^{-1}, but there is a local maximum in the vicinity of 970 MHz (**Figure 8**). One should note that the value of this maximum, in contrast to the lower frequencies, depends considerably on the existence of load at the ground of body. So, in the case of fully conducting ground, the WBA-SAR achieves 58.9 W·kg^{-1}, and in the case of the dielectric rubber substrate it grows up to 96.1 W·kg^{-1}. The first maximum achieves at the frequency 968.2 MHz, and the senond one at the frequency 967.8 MHz, respectively.

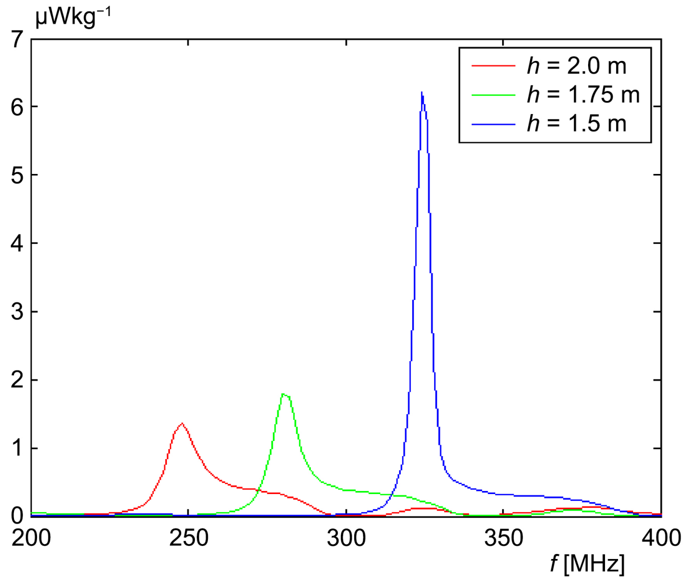

Figure 7. The values of WBA-SAR versus the frequency in the higher frequency range.

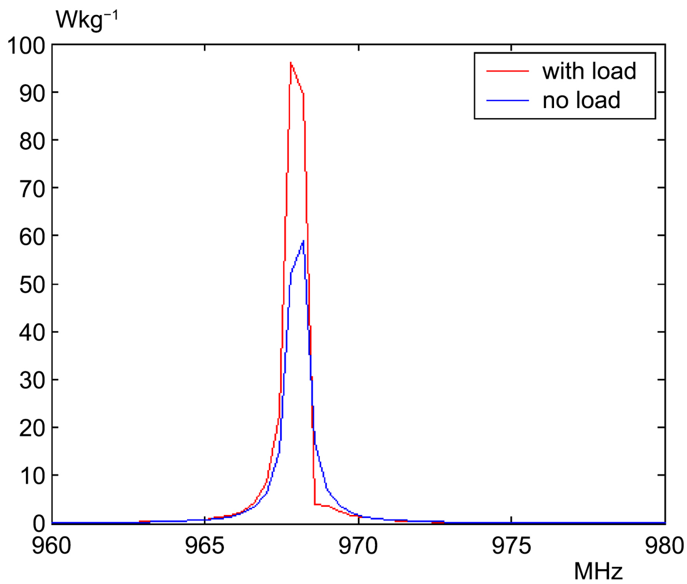

Figure 8. The values of WBA-SAR at the vicinity of frequency of 970 MHz, $h = 2.0$ m, $\varepsilon_r = 3.5$.

The respective values of current $I_z(h/2)$ are shown in **Figure 9**. In contrast to the values of the WBA-SAR, the characteristics of current are more wide and the maxima are not so sharp. The attained values in the considered vicinity of frequencies are larger than that, attained at the lower frequencies. And the maxima are 0.044 A and 0.057 A, respectively. As in the case of the WBA-SAR, the values of current grows considerably, if to compare with that corresponds to the case of the lower frequencies.

The calculations carried out in the range beyond the frequencies of 1200 MHz show that next maximum appears in the frequency vicinity of 1400 MHz, and it exceeds considerably that is attained in vicinity of 970 MHz. but such calculation can not be characterized as the correct, because the condition $ka \ll 1$, which is applied for the assessment of the applicability of the model of the linear antenna for evaluation of the impact of EM field on the human body for the frequencies larger than 1200 MHz, becomes invalid.

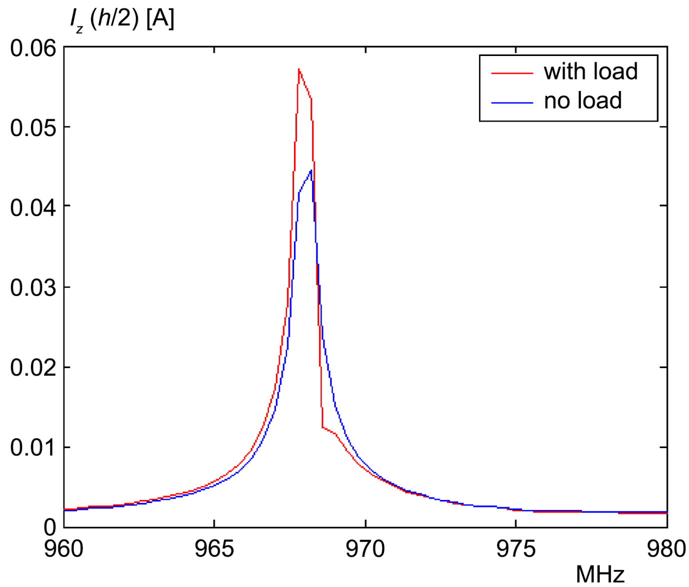

Figure 9. The values of $I_z(h/2)$ at the vicinity of frequency of 970 MHz.

3.4. Calculation of the Resonant Frequencies

The properties of the resonant frequency depends on the physical parameters of human body is shown in **Figure 10** and **Figure 11**. Formula (19) allows determining the resonant frequencies in the range up to 46 MHz. The dependence on the height h and weight W has similar character; and the calculated range of studied frequencies is from 30 MHz up to 45 MHZ.

In **Figure 10**, the dependence of f_{res} on the height h of body is presented for the different weights of body. One can see that the resonant frequency decreases when the height h grows. Simultaneously, this value decreases as well, if weight W grows. The values of resonant frequencies in the points $h = 1.50$ m, $h = 1.75$ m, and $h = 2.00$ m correspond that determine the maximal values of $I_{1z}(h/2)$ and WBA-SAR in **Figure 1** and **Figure 4**.

The dependence of f_{res} on the weight W of body is shown in **Figure 11**. Similarly to the previous data, the value of f_{res} decreases when weight W grows; and the maximal values of f_{res} are attained at $h = 1.5$ m. The obtained data allow determining the values resonant frequencies that have the greatest impact on the values of SAR for individual with specific anthropological parameters. The general conclusion is that the region of resonant frequencies moves to lower values when the height h and weight W grows.

The proposed approach to determine the resonant frequencies can not be applied for the higher frequencies because it contains a series of simplifications, which were applied to get the relation (15), (16), and final formula (17) for the resonant frequency. This explained by the fact that the relation between the Bessel functions $J_0(\kappa a)$ and $J_1(\kappa a)$ does not remain constant, therefore the value of (16) can not be considered as constant as well. More exact consideration demonstrates that the resonant frequency for the higher range can be calculated in the case very hard limitations.

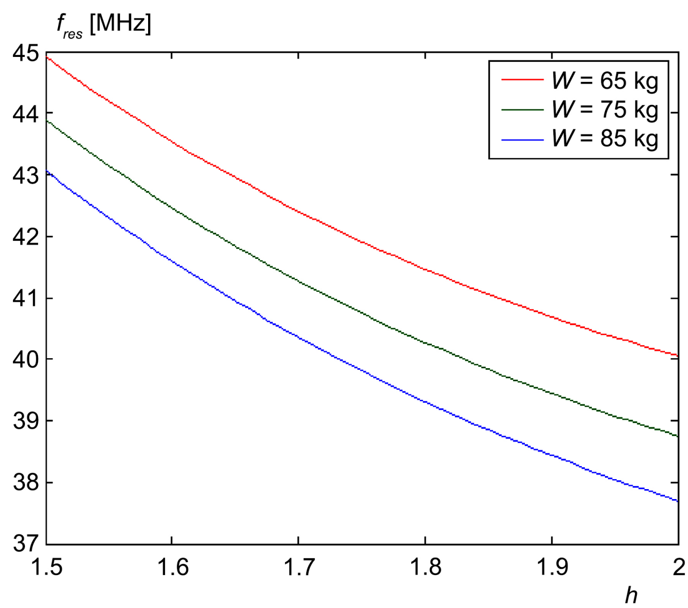

Figure 10. The values of f_{res} versus the height h of body.

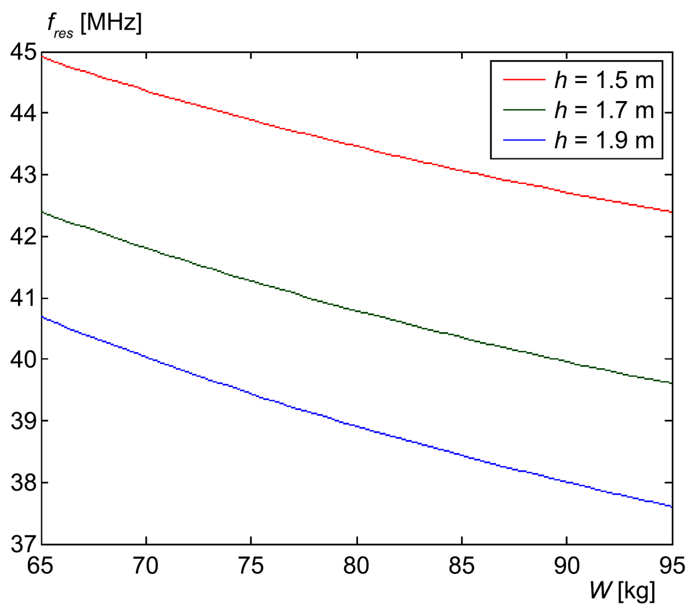

Figure 11. The values of f_{res} versus the weight W of body.

4. Discussion

The calculations of the WBA-SAR values in the wide range of frequencies based on the model of linear antenna demonstrate very different properties of the induced axial currents in the antenna, which models the human body in the stand position. So, the values of the WBA-SAR at the lower frequencies up to 400 MHz are very low and they do not exceed several tens of μW·kg^{-1}. The completely different situation is at the higher frequencies. In the range of frequencies from 800 MHz up to 1200 MHz there is one valuable maximum of the WBA-SAR only. Of course, its value depends on the amplitude E^{inc} of EM field, the biological properties of human body tissues, and the thickness of the rubber substrate. If to refer to **Figure 8**, one can conclude that for the considered values of the human body parameters, the WBA-SAR for the case of fully conductive body counts 96.1 W·kg^{-1}, this value is larger than that is allowed by the ICNIRP [2] for the considered ranges of frequencies. Even in the case of the ideal conducting substrate, this value is equal to 58.9 W·kg^{-1}, which is tens of times higher than the permissible values set by ICNIRP. The computations show that the value of WBA-SAR maximum depends on the value of incident wave E^{inc} in a great extent. For example, if to decrease the E^{inc} in the times, the maximum WBA-SAR decreases up to 0.96 W·kg^{-1}. This is because that the E^{inc} is contained in two terms in formula (1) for calculation of $I_z(z)$. Such characteristics of WBA-SAR are confirmed also by the experimental data received in [26].

5. Conclusion

The impact of the EM wave irradiation on the human body was analyzed using the model of an equivalent cylindrical antenna in the frequency range up to 200 MHz. The case of normal plane incidence wave is considered. The equivalent representation of the human body model in the form of a cylindrical antenna is simplified in accordance with the results of the FDTD method for three real anthropological voxel models. The impact of the height, weight, and dielectric properties of the human body on the WBA-SAR value is demonstrated. The approach proposed is applicable for studying the influence of EM radiation in the considering frequency range up to 200 MHz and beyond.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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