Characterizing the Human Body as a Monopole Antenna

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Characterizing the Human Body as a Monopole Antenna

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***Abstract*—This paper, for the first time, fully characterizes the human body as a monopole antenna in the frequency range of 10 - 110 MHz, which contains the resonance frequency of the human body. The human body is represented by an equivalent cylindrical monopole antenna grounded on a highly conductive ground plane that is analysed based on the three-term approximation method. The reflection coefficient is measured using a human subject as a monopole antenna. Measurement results show that the theoretical predictions are in reasonable agreement. It is found that the human body resonates between 40 - 60 MHz depending on the posture of the body when it is fed by a 50 Ω impedance system at the base of the foot. A minimum reflection coefficient of -12 dB is measured that demonstrates that the human body can be potentially used as an antenna. Theoretically, it is predicted that the human body can be an efficient antenna with a maximum radiation efficiency reaching up to 70 %, which is supported by measurement results found in the literature.**

***Index Terms*—human body, human body antenna, monopole antenna, cylindrical antenna, three-term approximation, resonance frequency, radiation efficiency, reflection coefficient, SAR**

I. Introduction

THE interaction of radio frequency (RF) electromagnetic fields with the human body has been the main interest for a large number of research. Part of these studies centered on the use of this interaction for medical applications. Other studies focused on the effect of electromagnetic fields on the human body, which were primarily driven by the growing concern raised in the society about the possible adverse effects of electromagnetic fields. Additionally, other studies also paid particular attention on the effect of the human body on antennas that operate inside or in the vicinity of the human body, such as, implanted and wearable antennas. Aside from the brief mention of the analogy between the whole human body and a quarter wave monopole antenna in few of these studies, a comprehensive characterization of the human body as a monopole antenna is not available in the literature.

In the field of RF dosimetry, the mechanism of RF energy absorption inside the human body has been exhaustively studied. For example, extensive early studies on RF dosimetry conducted by Gandhi [1] and others reported that the RF power absorbed inside the human body depends on the orientation of the incident electromagnetic field, its frequency, the presence of reflectors in the environment, and the posture of the human body. The primary focus of these studies were quantifying the amount of RF power absorbed by the human body. In these studies, important antenna characteristics of the human body were identified, such as, the frequency at which maximum RF power is absorbed in the whole body of a man in free space or in a man standing on perfectly conducting ground. It has been reported that the frequency at which maximum RF energy dissipates inside the whole body of a man standing on perfectly conducting ground, due to a vertically polarized plane wave, is close to the resonance frequency of a quarter wave monopole antenna that has the same height as the human subject [2]. This frequency, which is loosely termed as 'resonance frequency' in most RF dosimetry articles, not only depends on the height of the human subject, but also on the weight and gender of the subject. Even though such prior studies centered on quantifying the amount of RF power absorbed inside the human body; little has been reported about the comprehensive characterization of the human body with the objective of utilizing it as an antenna. The main theme of this paper is characterizing the human body as a monopole antenna by quantifying the antenna performance indicators, such as, the reflection coefficient and radiation efficiency of the human body, which have not been covered by previous studies.

Nowadays, the most common trend of computing the dissipated RF power inside the human body utilizes the finite-difference-time-domain (FDTD) algorithm based on computations of high resolution realistic voxel models of the human body [3]. Other prior studies used the cylindrical antenna model of the human body to study RF dosimetry. King applied a simplified form of the three-term approximation method to calculate the induced axial current inside the cylindrical antenna model of the human body [4], [5], [6]. In a related study, Poljak *et al.* implemented the method-of-moments (MoM) approach to calculate the axial current inside the thick-wire model of the human body [7]. Recently, we have applied the cylindrical antenna model of the human body using the three-term approximation to investigate the antenna effect of the human body on intrabody communication [8] and to analyse the whole-body averaged specific absorption rate [9].

Notable experiments, in attempt to characterize the human body as a monopole antenna, were carried out by Andresen *et al.* [10]. From the measured admittance of the human body as a monopole antenna, it was concluded that the human body does not resonate within the frequency range of 30-70 MHz. This contradicts the results in a large number of RF dosimetry computations and measurements that showed the whole-body resonance frequency of the human body is within the same frequency range. The reason for this could be the fact that the measured conductance is affected by the parasitic impedance between the foot and the ground. For the experimental setting used in [10], this parasitic impedance is so large that only a very weak resonance was observed

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between 30-70 MHz. By using a similar experimental setup, we were able to see a strong resonance at frequencies higher than 70 MHz. By decreasing the foot to ground separation, a strong resonance of the measured conductance can be observed within the frequency range 30-70 MHz. In [10], the authors also estimated the radiation efficiency of the human body as a monopole antenna by comparing gain measurements with that of thin-wire whip antennas. This second result is in reasonable agreement with our theoretical predications as shown later.

Other studies have made use of saline filled cylindrical models of the human body to measure the induced ankle current [11]. Similarly, a practical approach of using a monopole equivalent antenna of the human body was also proposed to measure the ankle current [12]. Despite the fact that all prior studies have focused on calculating or measuring the induced axial current inside the human body, none of them have fully characterized the human body with the essence of applying it as an antenna.

Presently, studies have demonstrated that the total axial induced RF current in the body, when the human body is irradiated by vertically polarized plane wave, is less affected by the change in cross-sectional size of the body, but behaves more like the axial current distribution in a cylindrical monopole antenna [11], [13]. These studies also showed that significant variations of the axial current density exist along the height of the body. This is due to the fact that large axial current density is developed in the cross-section of the body where there is small volume of conductive tissues, such as the knee and ankle. This is the basis of some studies that claim the local specific absorption rate (SAR) limit set by International Commission on Non-Ionising Radiation Protection (ICNIRP) [14] might be exceeded at the recommended exposure reference levels, at such parts of the body [2]. Therefore, the use of a homogenous cylindrical monopole antenna model of the human body is justifiable to characterize the whole human body in a standing posture. Such representation is more relevant to analyse the axial standing waves induced inside the human body that have wavelengths much larger than the body length. This is true for the frequency range we are interested in, which is lower than 110 MHz for a cylinder representing a human subject of height 1.76 m, as shown later. Moreover, such an approach has the advantage of simplicity and flexibility, to characterize the human body as antenna, compared to widely used methods, such as, the FDTD computations on realistic voxel models of the human body.

This paper characterizes the human body as a monopole antenna for the frequency range of 10 - 110 MHz. The human body is represented as a cylindrical monopole antenna that is analysed based on the three-term approximation method. The parameters of the cylindrical monopole antennas are defined based on the comparison with the FDTD based computation results of the total absorbed RF power inside the voxel models of the human body. Using these parameters, an expression for total induced axial current inside the human body is developed, which is used to characterize the human body as a receiving or transmitting antenna. The theoretical radiation efficiency and the reflection coefficient are used to determine the performance of the human body as a monopole antenna. The theoretically predicted results were compared against experiments that used a human subject to measure the reflection coefficient and radiation efficiency.

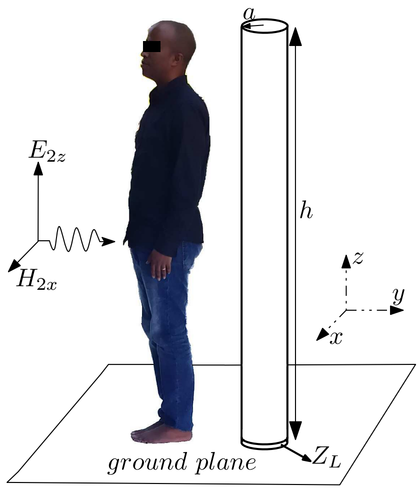

Fig. 1. The equivalent cylindrical monopole antenna of a person standing on a highly conductive ground. Z_L is the load impedance due to the space (shoes) between the foot and the ground.

II. Theory

Due to the conductive nature of the body, at the frequency range of interest, the induced axial fields are not distributed uniformly at a given cross-section. In other words, the frequency range we are interested is high enough that skin-effects cannot be ignored. The skin-effect phenomenon is incorporated into the model by considering the field distribution in the cross-section of a very long conductive cylinder of radius a, complex conductivity σ_ω^* and permeability μ_0. Assuming, only the axial component of a rotationally symmetric magnetic vector potential $A_{1z}(\rho, z)$ is maintained along its axis, the resulting wave equation can be solved as

$$A_{1z}(\rho, z) = DJ_0(\kappa\rho)\left(C_1 \cos\gamma z + C_2 \sin\gamma z\right) \quad (1)$$

where D, C_1, and C_2 are constants; J_0 is the zeroth-order Bessel function; $\kappa^2 = k_1^2 - \gamma^2$; $k_1 = \sqrt{-j\omega\mu_0\sigma_\omega^*}$; and $\gamma = \beta$ - $j\alpha$ is the complex propagation constant along the z-axis. From the boundary condition of the tangential magnetic fields at the surface of the cylinder, it can be shown that the total axial current $I(z)$ in the cylinder is

$$I(z) = C_1 \cos\gamma z + C_2 \sin\gamma z. \quad (2)$$

For the case of our equivalent cylindrical representation of the human body, the axial current should have a similar general form as the expression in (2) with additional terms to amend the effect of its finite length.

From the above expressions, the skin-effect, which was represented by the transverse distribution of axial field quantities, can be expressed based on the axial current density $J_{1z}(\rho, z)$ as

$$J_{1z}(\rho, z) = \frac{I(z)\kappa}{2\pi a}\frac{J_0(\kappa\rho)}{J_1(\kappa a)} \quad (3)$$

where J_1 is the first-order Bessel function. Also, the surface impedance per unit length of the cylinder z^i can be defined as

$$z^i = \frac{\kappa}{2\pi a \sigma_\omega^*} \frac{J_0(\kappa a)}{J_1(\kappa a)}. \tag{4}$$

The expressions of the axial current density and the surface impedance per unit length of the equivalent cylindrical monopole antenna representing the human body were defined to be the same as the expressions in (3) and (4), respectively.

A. The Induced Axial Current

The human body can be completely characterized as a receiving or transmitting antenna from the induced currents in the body. The problem of computing the induced currents can be simplified by considering a typical scenario of a vertically polarized plane wave illuminating a human subject standing on a highly conductive ground, as shown in Fig. 1. For this specific case, we assumed that the axial current induced by the vertically polarized electric field is dominant. Other characteristics of the human body as a receiving or transmitting antenna, such as the antenna impedance, radiation efficiency and reflection coefficient, can be derived from the expressions of the axial current. The problem is further simplified by using an equivalent cylindrical monopole antenna representation of the human body.

We assumed that a time-harmonic vertically polarized incident plane wave illuminated a cylindrical monopole antenna of height h and radius a, grounded on highly conductive infinite plane, that induced an axial current density of a form similar to the expression in (3). From antenna theory [15], it is well-known that the surface axial magnetic vector potential $A_{2z}(a, z)$ due to the axial current density can be expressed as

$$A_{2z}(a, z) = \frac{\mu_0}{4\pi} \int_{V'} J_{1z}(\rho', z') \frac{e^{-jk_2 r}}{r} dv' \tag{5}$$

where $k_2 = \omega\sqrt{\mu_0 \epsilon_0}$ is the free space wave number. Applying the three-term approximation conditions ($k_2 a \ll 1$, $h \gg a$, and $k_2 h \leq \frac{5}{4}\pi$) [16], [17], the expression of r reduces to

$$r = \sqrt{(z - z')^2 + a^2} \tag{6}$$

so that the expression in (5) simplifies to

$$A_{2z}(a, z) = \frac{\mu_0}{4\pi} \int_{-h}^{h} I_{1z}(z') \frac{e^{-jk_2 r}}{r} dz' \tag{7}$$

where $I_{1z}(z')$ is the induced axial current. Applying the boundary conditions of the axial electric fields on the surface of the cylinder, the scattered axial electric field on the surface of the cylinder is related to $A_{2z}(a, z)$ using the one-dimensional wave equation [8], [16], [17] as

$$\left(\frac{\partial^2}{\partial z^2} + k_2^2\right) A_{2z}(a, z) = j\frac{k_2^2}{\omega} \left[I_{1z}(z) z^i - V_0 \delta(z) - E_0\right] \tag{8}$$

where E_0 is the incident axial electric field on the surface of the cylinder and V_0 is the voltage drop on a load at the base of the cylinder with the resulting electric field approximated by the delta-gap model.

An expression for $I_{1z}(z)$ can be derived from (8) using the three-term approximation method [8], [16], [17] as

$$I_{1z}(z) = V_0 v(z) + U_0 u(z) \tag{9}$$

where

$$V_0 = -I_{sc}(0) \frac{2Z_A Z_L}{2Z_A + Z_L} \tag{10}$$

$$U_0 = \frac{E_0}{k_2} \tag{11}$$

$$v(z) = \frac{j2\pi k_2}{\zeta_0 \gamma \Psi_{dR} \cos(\gamma h)} \Big[\sin\gamma(h - |z|) + T_U(\cos\gamma z - \cos\gamma h) + T_D(\cos\tfrac{1}{2}k_2 z - \cos\tfrac{1}{2}k_2 h)\Big] \tag{12}$$

$$u(z) = \frac{j4\pi}{\zeta_0} \Big[H_U(\cos\gamma z - \cos\gamma h) + H_D(\cos\tfrac{1}{2}k_2 z - \cos\tfrac{1}{2}k_2 h)\Big] \tag{13}$$

Z_A is the input impedance of the monopole antenna; Z_L is load impedance at the base of the cylinder; $I_{sc}(0) = U_0 u(0)$ is the short-circuit current at the base of the cylinder when $Z_L = 0$; and $\zeta_0 = 120\pi\ \Omega$ is the free space impedance. The imperfectly conducting characteristics of the cylinder is defined by γ as

$$\gamma^2 = k_2^2 \left(1 - \frac{j4\pi z^i}{k_2 \zeta_0 \Psi_{dR}}\right). \tag{14}$$

The coefficients in the (12), (13) and (14) are calculated for each frequency by numerical computations of the integrals given in our previous paper [8].

The characteristics of the cylinder as a transmitting antenna can be easily derived from the expression of the total induced axial current of the receiving antenna when the cylinder is driven at the base with electromotive force V_0. Thus, the total induced axial current $I_{1z}(z)$ for the transmitting equivalent cylindrical monopole antenna can be expressed as

$$I_{1z}(z) = 2V_0 v(z). \tag{15}$$

B. The Cylindrical Antenna Parameters

In our previous studies [9], [18], we employed the equivalent cylindrical antenna representation of the human body to accurately predict the FDTD computed whole-body averaged specific absorption rate on 14 realistic high resolution voxel models that were reported in the literature. We found that the parameters of the equivalent cylindrical antenna (a, h, and σ_ω^*) depended on gender and age. In this study, since we used an adult male human subject for the experimental measurement, the parameters defined for the adult male voxel models were used to characterize the equivalent cylindrical antenna. Accordingly, the expression for the radius a was derived as

$$a = \sqrt{\frac{5m}{\pi \rho_m h}} \tag{16}$$

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where m (kg) is weight of the human subject, h (m) is height of the subject and ρ_m = 1050 kgm^{-3} is the average density of the human body. In [9], [18], it was assumed that the cylinder consists of a suspension of spherical particles that was analysed based on the Maxwell-Wagner effective medium theory. Thus, the complex conductivity of the cylinder was related to the human body parameters as

$$\sigma_\omega^* = 0.58 f_m \frac{2x}{3-x} \sigma_m^* \tag{17}$$

where f_m is the fraction of muscle tissue by mass that can be approximated as 0.43 for adult males with normal body-mass-index (18.5-24.9) and σ_m^* is the complex conductivity of muscle tissue calculated from the 4-Cole-Cole dispersions parameterized by Gabriel *et al.* [19]. The factor x is a function of the lean-body-mass that characterizes the total body water volume and it was defined for adult males as

$$x = 0.321 + \frac{1}{m}(33.92h - 29.53). \tag{18}$$

The height of the cylinder was defined to be the height of the human subject h.

In order to determine how well the equivalent cylindrical monopole antenna predicts the FDTD based computations results on realistic voxel models, the total absorbed RF power in a human subject calculated using the two methods was compared. The total absorbed power P_{abs} for an incident electric field E_0 illuminating a human subject grounded on a highly conductive ground is defined as

$$P_{abs} = \frac{1}{2} R_c \int_0^h |U_0 u(z)|^2 dz \tag{19}$$

where R_c is the real part of the total impedance per unit length Z_c of the cylinder that can be derived as

$$Z_c = \frac{1}{\pi a^2 \sigma_\omega^*}. \tag{20}$$

The comparison of the total absorbed power calculated using the FDTD computation on realistic voxel model of a male adult of height h= 1.76 m and weight m= 73 kg [2] and our three-term approximation approach (19) on its equivalent cylinder with parameters defined using (16) and (17) is shown in Fig. 2.

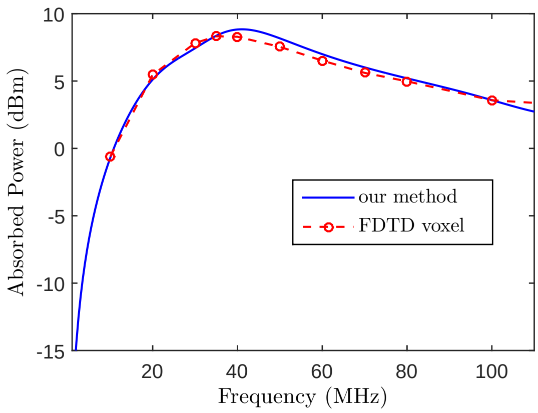

Fig. 2. Comparison of the calculation results of the total absorbed RF power in the body of a grounded human subject of h=1.76 m and weight m=73 kg for an incident electric field E_0 of 1 V/m r.m.s.

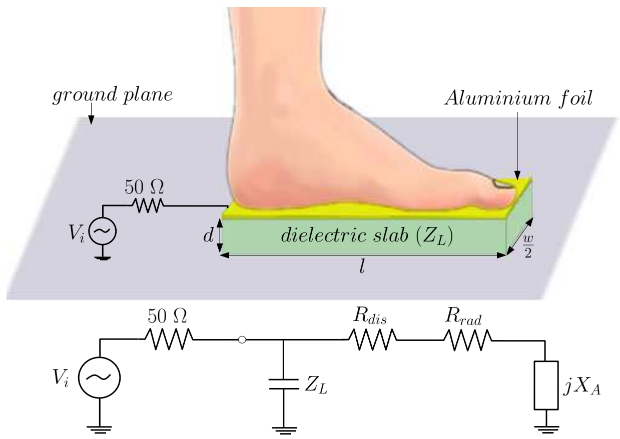

Fig. 3. The diagram shows the typical setup of feeding the human body as a cylindrical monopole antenna and its corresponding equivalent circuit representation. A single foot is shown for clarity.

C. Radiation Efficiency and Reflection Coefficient

The radiation efficiency η_r and reflection coefficient $|S_{11}|$ are important parameters that demonstrate the potential utilization of the human body as an antenna. The analysis of these parameters can be facilitated by the representation of the equivalent cylindrical monopole antenna with the corresponding equivalent circuit. We considered the specific case of a person standing bare foot on a dielectric slab of thickness d, area A and relative permittivity ϵ that is located on the surface of a highly conductive ground plane, as shown in Fig. 3. A thin Aluminium sheet is placed on top of the dielectric slab for the subject to rest the feet; and it is excited by an RF source via a 50 Ω transmission line that is grounded on the highly conductive ground plane. The reason such setting was chosen is, unlike conventional monopole antennas, the parasitic impedance Z_L due to the base of the foot and the ground cannot be ignored when considering the human body as a monopole antenna. This parasitic impedance is small due to the large surface area of the foot so that part of the RF current couples to the ground via this impedance. The parasitic impedance is related to the impedance due to the sole of shoes. Therefore, the equivalent circuit representation of the cylindrical antenna includes this parasitic impedance, as shown in Fig. 3.

From Fig. 3, it can be seen that the human body antenna impedance Z_A was represented by its components as

$$Z_A = R_{dis} + R_{rad} + jX_A \tag{21}$$

where R_{dis} represents the power dissipated P_{dis} in the human body due to conduction and dielectric loss of the human body, R_{rad} represents the radiated power P_{rad}, and X_A represents the power stored in the near fields of the human body. The antenna impedance Z_A can be easily calculated from the expression of the axial current (15) by assuming an input voltage V_0 at the terminals of the antenna. The antenna

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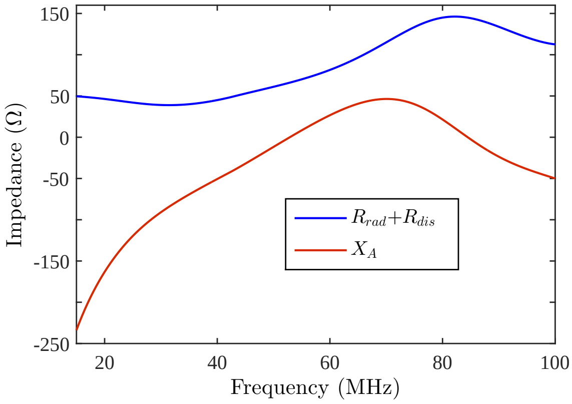

Fig. 4. The antenna impedance Z_A calculated for a cylindrical monopole antenna representing a human subject of height h=1.76 cm and weight m=73 kg.

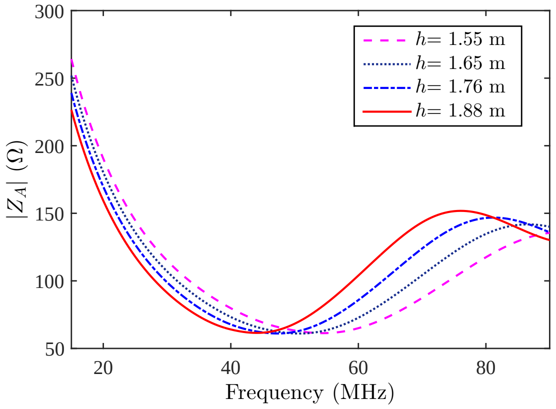

Fig. 5. The magnitude of antenna impedance versus height of the cylindrical monopole antenna representing different human subjects that have the same body-mass-index of 23.56.

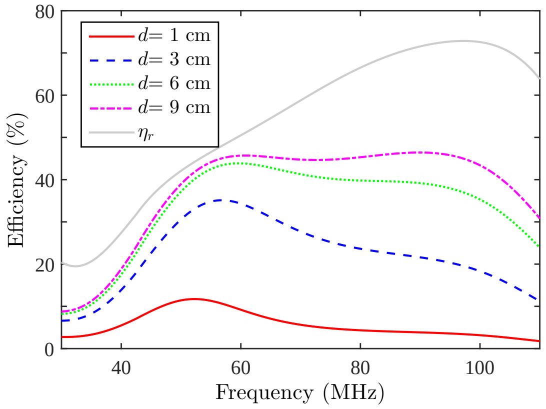

Fig. 6. The theoretical radiation efficiency η_r and the total efficiency η_t for different thicknesses d of the dielectric slab (ϵ= 3, area= 22x30 cm^2) placed underneath the cylindrical monopole antenna representing a human subject of height h=1.76 m and weight m=73 kg.

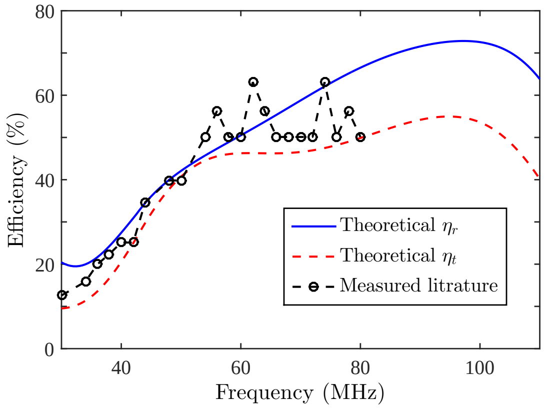

Fig. 7. Comparison of η_r and η_t with the measured radiation efficiency found in [10]. η_t was calculated based on the experimental setting in the literature; Z_0= 50 Ω, parameter for Z_L are ϵ= 1, A=π(0.15)^2 m^2, and d= 0.1 m.

impedance Z_A is

$$Z_A = \frac{1}{2v(0)}. \quad (22)$$

The antenna impedance calculated for an equivalent monopole antenna representing a human subject of height h= 1.76 m and weight m= 73 kg is shown in Fig. 4. Fig. 5 shows the relationship between the variation in the dimension of the equivalent cylindrical monopole antennas and the magnitude of the antenna impedance. The magnitude of the antenna impedance was calculated for different equivalent cylindrical monopole antennas representing human subjects of different height with similar body-mass-index of 23.56. Minimum of $|Z_A|$ shifts to lower frequencies as the height of the monopole antenna increases, suggesting that a tall human subject causes lower resonance frequency.

The radiation efficiency η_r is defined as the ratio of the power radiated to the total antenna input power P_{in} as

$$\eta_r = \frac{P_{rad}}{P_{in}} = 1 - \frac{P_{dis}}{P_{in}} = 1 - \frac{R_c}{R_{rad} + R_{dis}} \int_0^h \frac{|v(z)|^2}{|v(0)|^2} dz \quad (23)$$

where P_{in}= P_{rad}+P_{dis}. The effect of the impedance mismatch between the input circuit and the antenna can be characterized by the total efficiency η_t defined as

$$\eta_t = \eta_r \left(1 - |\Gamma|^2\right) \quad (24)$$

where Γ is the reflection coefficient. The reflection coefficient in the case of Fig. 3 is influenced by the parasitic impedance Z_L; therefore, it can be obtained as

$$\Gamma = \frac{Z_{eq} - Z_0}{Z_{eq} + Z_0} \quad (25)$$

where Z_0= 50 Ω is the output impedance of the feeding circuit and Z_{eq} is the equivalent impedance of Z_A and Z_L in parallel.

From Fig. 6 and Fig. 4, it can be seen that the theoretical radiation efficiency increases with frequency, which tends to follow the pattern of the real part of the antenna impedance $R_{rad} + R_{dis}$. This is because the real part of the total impedance of the cylinder per unit length R_c changes slowly within the frequency range of interest. The theoretical efficiency suggests that the human body has a high radiation efficiency, up to 70 %, for higher frequencies (between 90-100

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MHz), provided the RF current is coupled to the base of the foot efficiently. For the particular scenario considered here, the total efficiency η_t is the appropriate parameter to characterize the performance of the human body as a monopole antenna, since it captures the effect of the dielectric slab (shoes) underneath the foot. Fig. 6 shows that as the thickness d of the dielectric slab increases, the parasitic impedance Z_L increases, causing more RF current to excite the base of the foot so that the total efficiency increases. Therefore, the parasitic impedance should be maximized to increase the total efficiency or gain. In practice, however, the radiation efficiency is smaller due to losses such as the power dissipated through the imperfectly conducting ground.

The calculated theoretical radiation efficiency of the human body is close to the measured radiation efficiency of a seawater monopole antenna, a maximum of 75 $\%$, in the frequency range of 40-200 MHz [20]. In other studies [11], [21], measurements on saline based equivalent cylindrical monopole antennas of the human body were used to estimate the induced ankle current computed using a realistic voxel model of the human body. This suggests that the human body can be represented by a saline filled cylindrical monopole antenna. Therefore, the calculated theoretical radiation efficiency being close to the measured radiation efficiency of the seawater monopole antenna is a plausible estimate.

In order to determine how accurate our predicted theoretical radiation efficiency is, η_r and η_t were compared to a measured radiation efficiency found in the literature. In [10], the radiation efficiency of a human body as a monopole antenna was estimated from gain measurements relative to whip antennas. By using the parameters used in the measurement, we predicted the measured radiation efficiency in a reasonable accuracy as shown in Fig 7. It can be seen that, at 60 MHz, half of the input power is dissipated inside the body. More interestingly, it can be inferred that the human body as a monopole antenna has a maximum theoretical radiation efficiency, about 70 $\%$, in the FM radio band.

The other antenna performance indicator is the reflection coefficient that can be represented in the s-parameter form as

$$|S_{11}|(dB) = 20\log_{10}(|\Gamma|). \tag{26}$$

Fig. 8 shows the theoretical reflection coefficient for the equivalent cylindrical monopole antennas of different height representing human subjects of similar body-mass-index. The reflection coefficient was calculated ignoring the parasitic impedance Z_L and assuming the antenna was fed by a 50 Ω system. As expected, the resonance frequency shifts downwards as the height of the antenna increases with a minimum reflection coefficient $|S_{11}|$ about -17 dB.

The effect of the dielectric slab on the reflection coefficient is depicted in Fig. 9; it can be seen that as the thickness d of the dielectric increases the reflection coefficient decreases with the resonance frequency increasing slightly. The reflection coefficient also shows that a large value of the parasitic impedance improves the performance of the human body as antenna.

It should be noted that the term ‘resonance frequency’ used in this paper is to indicate the frequency where the

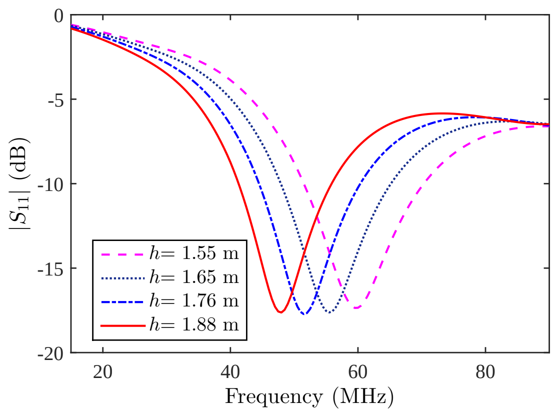

Fig. 8. Comparison of the calculated reflection coefficients for cylindrical monopole antennas representing human subjects of different height and the same body-mass-index of 23.56.

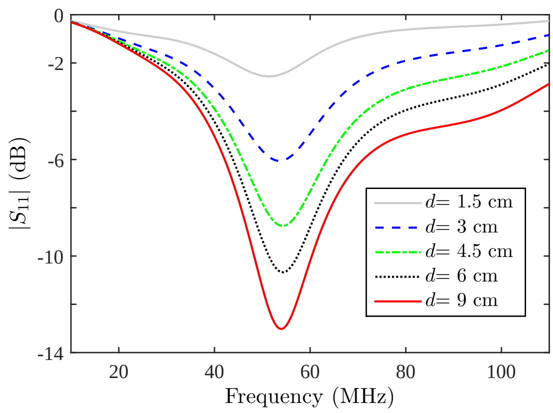

Fig. 9. Comparison of the calculated reflection coefficients for different thicknesses d of the dielectric slab (ϵ= 3, area= 22x30 cm^2) placed underneath a cylindrical monopole antenna representing a human subject of height h= 1.76 m and weight m= 73 kg.

lowest reflection coefficient occurred based on (26). In RF dosimetry, the term ‘resonance frequency’ is often used to indicate the frequency at which maximum power is absorbed inside the whole body. Assuming the parasitic impedance Z_L is neglected in (25), it can be seen that the calculation of the reflection coefficient involves the antenna impedance Z_A and the device output impedance Z_0. But in the case of calculating the total absorbed power, only the antenna impedance Z_A is used; therefore, the two resonance frequencies are not identical. For example, in our previous study [18], we were able to formulate the resonance frequency of the total absorbed power, inside a grounded human body, using the height and weight of the person as parameters. The proposed formula accurately predicted the FDTD computed results from using realistic voxel models, which were developed by different research groups, representing different ages, gender, and race. The formula for the resonance frequency f_{res} in Hz is

$$f_{res} \simeq \frac{c}{4\pi}\left[1.742\left(\frac{\pi H}{W}\right)^{\frac{1}{2}} + \left(3.0345\frac{\pi H}{W} + \frac{4}{H^2}\right)^{\frac{1}{2}}\right] \tag{27}$$

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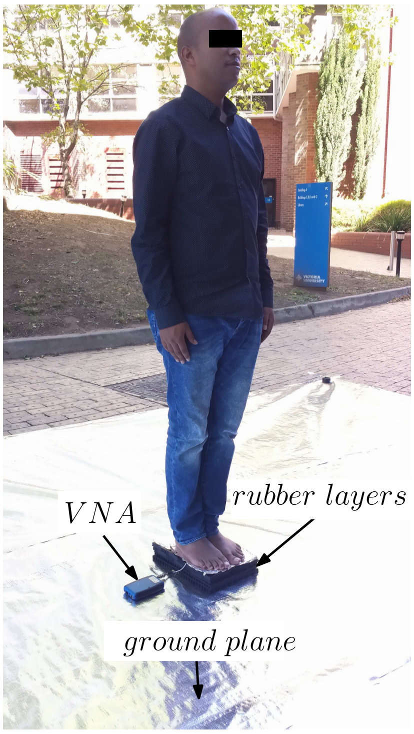

Fig. 10. The experiment setup with a human subject of height h= 1.76 m and weight m= 73 kg.

where H is height of the subject in meters; W is weight of the person in kilograms; and c is the speed of light in free space. For the human subject of height 1.76 m and weight 73 kg, the resonance frequency obtained from the reflection coefficient is approximately 50 MHz as shown in Fig. 8, whereas the resonance frequency of the maximum power absorption calculated from (27), for the same subject, is approximately 40 MHz. A formulation for the resonance frequency of the maximum power absorbed for a person in free space can be found in [9].

III. Experiment

In order to validate the theoretical predictions made about the performance of the human body as cylindrical monopole antenna, experimental characterization was carried out. The typical scenario considered in this study, which is shown in Fig. 3, was experimentally setup and important parameters were measured. A bare-foot human subject of height h= 1.76 m and weight m=73 kg stood on layers of rubber slabs (1.5 cm thick, 22 cm wide and 30 cm long each) with Aluminium foil placed on top, as shown in Fig. 10. The rubber layers were placed in the middle of a 4.5×5 m^2 Aluminium sheet that acted as the conductive ground plane. The signal was generated using a battery operating vector network analyser (VNA), which is capable of sweeping the frequency range of 1-200 MHz. The effect of radiating cables and human operator was eliminated by connecting the VNA and the measuring computer via a Bluetooth connection. The RF signal was fed to the Aluminium foil with a short coaxial cable with its shield attached to the ground plane. The rubber slabs were stacked to

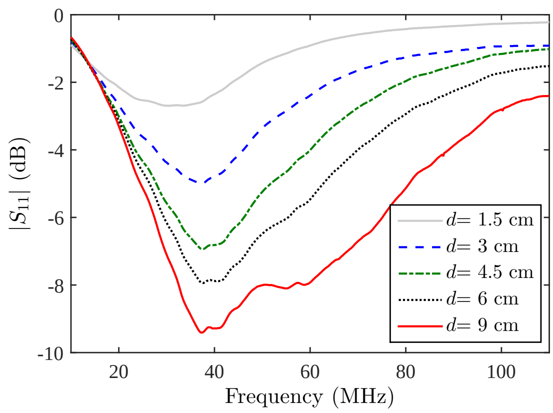

Fig. 11. The measured reflection coefficient for different thicknesses of the rubber layers (ϵ= 3, area= 22x30 cm^2) placed underneath the human subject.

create a variable thickness dielectric in order to see the effect of changing the values of the parasitic impedance.

The maximum output power of the VNA is 0 dBm, according to the specifications of the VNA, which is much smaller compared to the safety limit restricted by ICNIRP [14]. Taking the worst case, if we assumed all the power generated by the VNA is dissipated inside the body of the human subject, the Whole-Body Averaged Specific Absorbtion Rate (WBA-SAR) is $10^{-3}/73$= 137 μWkg^{-1}, which is much lower than the WBA-SAR limit set by ICNIRP, 0.4 Wkg^{-1} for occupational exposure. Even assuming the unlikely event that all the VNA output power is absorbed by 1 gm of the tissue of the human subject, the local SAR is equal to 137 mWkg^{-1}, which is still much smaller compared to the recommended limit for occupational exposure on the head and trunk, which is 10 Wkg^{-1}. For the frequency range of 100 kHz to 10 MHz, the ICNIRP limit is set based on the current density, which is defined as $f/100$ mA/m^2, where f is the frequency in Hz. At 1 MHz, taking the mean conductivity of muscle 0.5 Sm^{-1} and its density 1.06 kgm^{-3}, the power deposited in 1 gm of muscle due to the maximum permissible current density at this frequency is 100 mW, which is larger than the output power of the VNA. But, we know that it is unlikely that all the output power dissipates on a 1 gm tissue of the human subject; therefore, the experiment was safe to use a human subject.

The measured reflection coefficient for different thicknesses of the dielectric slab is shown in Fig. 11. Even though the theoretical reflection coefficient shown in Fig. 9 predicted the general behaviour of the experimental results, there are differences in the location of the resonance frequencies and the magnitude of the reflection coefficient. The resonance frequency predicted was near 50 MHz but the measurement results show resonance close to 40 MHz. One of the obvious causes of such differences is the fact that the human body is modeled by a cylindrical antenna that was analysed based on the three-term approximation. The other causes are experimental factors that were not included in the theoretical setup. One such factor is the effect of the Copper core of the coaxial cable used to connect the VNA to the Aluminium foil. In order

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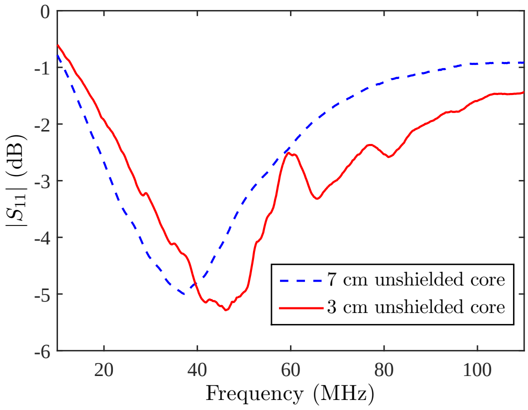

Fig. 12. Comparison of the effect of varying the length of the unshielded Copper on the measured reflection coefficient. The thickness of the rubber layer used was 3 cm.

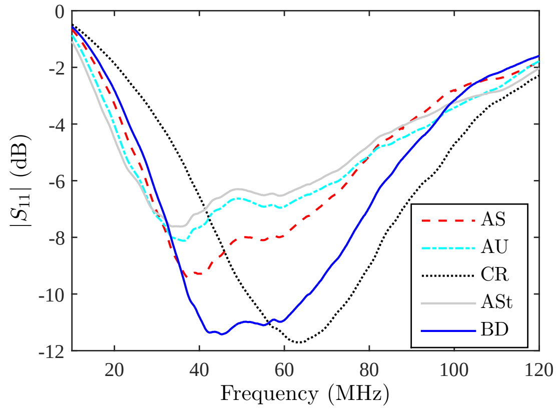

Fig. 14. The measured reflection coefficient when the subject posed different postures. AS= arms by side, AU= arms raised up, CR= crouching, ASt= arms stretched out, and BD= bending down. The thickness of rubber layer used was 9 cm.

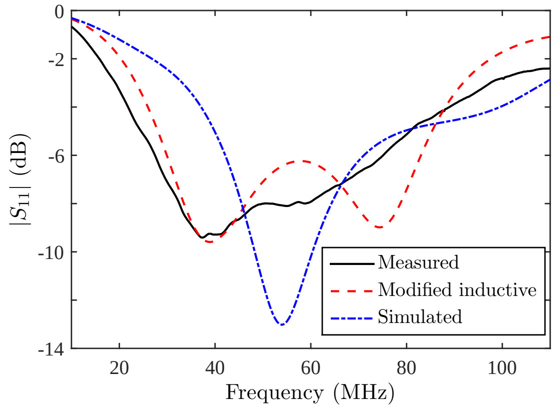

Fig. 13. Comparison of the measured reflection coefficient with the simulation results. The modified simulation represents the reflection coefficient calculated after adding a series inductive reactance representing the unshielded Copper core. The thickness of rubber layer used was 9 cm.

to accommodate the variable thickness of the dielectric layers and secure a good ground connection, part of the Copper core, 7 cm long, was left unshielded. We observed that shortening the size of the unshielded core shifts the resonance frequency upwards as shown in Fig. 12, which illustrates the difference when using a 7 cm and a 3 cm long unshielded cores. This is expected as a longer unshielded Copper core increases the total height of the radiating element in addition to the human body; therefore, it has the effect of shifting the resonance frequency slightly downwards. Another experimental factor that was not included in the theoretical setup was the additional impedance due to the unshielded coaxial cable and its connection with the Aluminium foil. Incorporating this impedance as a series inductive reactance between the feeding circuit and the load Z_{eq} of the theoretical setup shown in Fig. 3, the measurement results can be predicted better as shown in Fig 13. Fig. 13 shows the addition of a series inductive reactance, which represents the effect of the unshielded core, reduces the capacitive reactance of the Z_{eq}; thus shifts the resonance frequency lower.

Another interesting observation is the human body retains the impedance characteristics even for different postures. This was seen when the reflection coefficient was measured with the human subject in different postures as shown in Fig. 14. Lifting the arms high increases the total length of the radiating element, therefore the resonance frequency shifts downwards as shown in the measurement results. The measured reflection coefficients for stretching the arms out and lifting them high are slightly different with the former case shifting the resonance frequency a little downwards. When the subject crouched or bent down, the radiating length shortened; therefore, the resonance frequency shifted upwards. More interestingly, the reflection coefficient improved almost by 2 dB when crouching and bending down; this could be due to the increased surface area closer to the RF source.

Applying the human body as a transmitting antenna by coupling large RF power might not be ethical and also the power dissipated inside the human body might exceed the recommended limit. But, the human body can be used as a receiving monopole antenna for applications that involve low power electromagnetic fields or fields that are present in the environment. One such application is the use of the human body as a receiving antenna for RF energy harvesting. Currently, the interest in the area of RF energy harvesting is growing particularity in the field of self-sustained and autonomous sensor networks. Research focused on the ambient RF energy in the digital TV band because there is uninterrupted available broadcast power and also the antenna size required is relatively small. Several ambient RF energy surveys showed that the available power in the FM band is comparable or sometimes better than the available power in digital TV bands [22], [23], [24]. But the idea of designing an RF energy harvesting system in FM band has been abandoned for the primary reason that a larger antenna is required at this frequency band. By designing an optimal matching network, the human body might be used as antenna for RF energy harvesting in the FM band to power wearable or implanted antennas.

Another possible application of the human body as receiving antenna is in the area of far-field wireless power transfer to energize implants in the human body. As it known that the

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total axial current distribution in the human body, near the resonance frequency, has larger value close to the feet. It is also known that there is small amount of conductive tissue in the ankle; this implies that the current density in the vicinity of the ankle is very large compared to other parts of the body. The large current density at the ankle can be intercepted to power implants embedded in the lower legs. An implanted ferrite core toroidal transformer, in conjunction with a rectifying circuit, can be used to convert the RF current to a usable DC power. For such applications, the far-field power can be broadcasted from a source operating near the human body resonance frequency. The legal requirements of narrowband energy broadcasting can be met by employing the Industrial, Scientific and Medical (ISM) radio band at 40 MHz, which lies in the resonance frequency region of the human body.

IV. Conclusion

In this paper, the human body as a cylindrical monopole antenna has been characterized by using the equivalent cylindrical antennas that were analysed using the three-term approximations. Theoretically, it was found out that the human body can be an efficient radiating antenna with theoretical radiation efficiency reaching up to 70 % for the frequency range of 90 - 100 MHz. But, the total efficiency deteriorates when the human body is coupled to a 50 Ω system due to impedance mismatch, which can be improved with the design of an optimal matching network. In practical scenario, the efficiency decreases further due to the losses in the ground and the small values of the parasitic impedance due to shoes. It was also found that the human body resonates between 40 - 60 MHz with the magnitude of the reflection coefficient not much affected with different postures. Measurement results showed that crouching and bending down improved the magnitude of the reflection coefficient by 2 dB. The human body as a monopole antenna can be used for applications that use low RF power, such as RF energy harvesting and far-field wireless power transfer.

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