Thickness estimation of the subcutaneous fat using coaxial probe

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In this Letter, a non-invasive method for thickness estimation of the subcutaneous fat layer of abdominal wall is presented by using a coaxial probe. Fat layer has the highest impact on the averaged attenuation parameter of the abdominal wall due to its high thickness and low permittivity. The abdominal wall is modelled as a multi-layer medium and an analytical model for the probe is derived by calculation of its aperture admittance facing to this multi-layer medium. The performance of this model is then validated by a numerical simulation using finite-difference-time-domain (FDTD) analysis. Simulation results show the high impact of the probe dimension and fat layer thickness on the sensitivity of the measured permittivity. The authors further investigate this sensitivity by statistical analysis of the permittivity variations. Finally, measuring in different locations relative to the body surface is presented as a solution to estimate the fat layer thickness in the presence of uncertainty of model parameters.

1. Introduction: In-body communications have the potential to significantly affect the next generation of healthcare. In implantable medical devices such as endoscopy capsules or pacemakers, the medical data is transmitted wirelessly to an external unit for monitoring, diagnosis and therapeutic purposes. To design the communication systems for such wireless body area network, an appropriate propagation channel model is required. Precise parametric channel model calls for updated measurement of every case study.

Path loss and attenuation in human body have been modelled by many researchers. In most of these studies, the human body was assumed as a homogeneous transmission medium with constant attenuation coefficient (refractive index) [1, 2]. Other studies including the effect of age [3], uncertainty in the permittivity of the tissues [4] and the thickness of the layers in the form of adaptive or parametric models [5] advanced the propagation model. In [5], the abdominal wall is modelled as a multi-layer medium including skin, fat, muscle fascia and lumen, where each layer has its own permittivity and thickness. It is shown that by measuring (estimating) the thickness of fat layer and substituting its value in an adaptive path loss model, the modelling error can be reduced to a high degree. Fat layer is one of the thickest layers of the abdominal wall and its complex permittivity is five to ten times lower than the other tissues in Medical Implant Communication Service frequency band. Hence, it has the most impact on the effective permittivity of the abdominal wall.

Measuring the thickness of subcutaneous fat is a well-known issue in medical science. The conventional methods range from skinfold callipers (SC) and computed tomography (CT) to magnetic resonance imaging (MRI) and ultrasonography (US) [6]. The most widely used technique for measuring the thickness of subcutaneous fat is SC which is often used to obtain estimates of whole-body fat. Although this method is non-invasive and relatively inexpensive, accurate measurement might be difficult to attain in all individuals, especially in those with adipose tissue that does not separate well from the underlying muscle [7]. Although CT and MRI methods are the most accurate methods, they are expensive and have some practical and ethical constraints [8]. US devices, which estimate the thickness of fat by measuring the amount of reflected sound from tissues [9, 10], are portable and less expensive compared with CT and MRI devices. The disadvantages of this method are the limited accuracy and lack of standardisation for the measurement technique such that the results are highly dependent on the operator proficiency [10]. Selecting one of these methods depends on the situation and application. Some of the reported applications for measuring subcutaneous fat thickness are: estimating the obesity-related health risk [11], diabetes investigation [12], prediction of abdominal adiposity [8], assessing the risk for hepatic steatosis [9] and accessing the nutritional and dietary status of newborns [13].

This Letter investigates a novel method to estimate the thickness of subcutaneous fat layer using coaxial probes. In the coaxial probe, an electromagnetic (EM) wave is incident on the surface of the material under test (MUT) and the complex permittivity of the MUT is estimated by measuring the reflected wave. This method is non-invasive and low cost and the device is portable. The main characteristic of this method is that the frequency of carrier signal can be selected as the same of in-body communication systems. In in-body communication systems like capsule endoscopy, the transmitted power of EM wave between the transmitter and the receiver is modelled while in the coaxial probe, the reflected power of the same wave from the medium is measured. In other words, by considering the abdominal wall as a two-port network between the skin and the lumen, the reflected power (measured by probe) and the transmitted power (between in-body transmitter and on-body receiver) are the first and second scattering parameters, respectively. Some of uncertainties, such as difference in the permittivity of tissues in different experimental trials, impact the scattering parameters. Therefore, in channel modelling applications, where the thickness of fat layer is measured to be substituted in the model of communication channel, the developed method in this Letter has the advantage of taking into consideration some of the network uncertainties.

In measuring the permittivity of a medium using coaxial probe, the main assumptions are the homogeneity and semi-infinite depth of the medium under test. However, in biomedical applications, when the medium's thickness is less than the penetration depth of the probe, further layers influence the measurements [14]. For example, in the case of a multi-layer medium, the measured permittivity is the effective permittivity of the medium which is a function of permittivity and thickness of all layers in the penetration depth. This property could be helpful in applications that the parameters of the next layers are of interest. In [15], the authors connected a coaxial probe to the body skin and estimated the EM parameters of the fat layer as a risk factor of breast cancer. Alanen *et al.* [16] investigated the effect of thickness of the skin layer and the permittivity of the subcutaneous fat on the measured permittivity by the coaxial probe.

The objective of this Letter is to investigate the limitations and advantages of thickness estimation of the fat layer (as the second layer of the abdominal wall) using a coaxial probe. For this purpose we use two methods, analytical and numerical. In the analytical method, we follow the lead of [17] to calculate the admittance of the probe aperture and then the quasi-static method [18] to estimate the effective permittivity from the calculated admittance. The analytical method has lower computational complexity compared with the numerical method and is especially useful for the statistical analysis of the system. In the numerical method, finite-difference-time-domain (FDTD) analysis of the three-dimensional (3D) model of the system is performed in the SEMCAD environment [19]. This method is used to validate the results of the analytical model. In the performed simulations, the impact of fat layer thickness on the accuracy of the measurements and the effect of probe dimensions on the measurement sensitivity are investigated.

The rest of the Letter is organised as follows. In the next section, the analytical method for modelling the aperture admittance is described. Estimation of the complex permittivity by using an optimisation problem is also presented in Section 2. System modelling using numerical simulation is described in Section 3. Section 4 presents the simulation results of the sensitivity analysis of the measured permittivity to the variations of the fat layer thickness and probe dimension. Finally, Section 5 includes discussions and concluding remarks.

2. Coaxial probe terminated to layered dielectrics: In coaxial probes, the complex permittivity of a medium is estimated by measuring the reflection of a transmitted signal. To model the probe faced to a multi-layer medium in terms of effective permittivity and calculated admittance, we divide the modelling process into two steps: (i) calculating the equivalent admittance (or reflection coefficient) at the probe aperture as a function of the parameters of probe and multi-layer medium and (ii) estimating the effective permittivity from the calculated admittance. These two parts will be explained in the following subsections.

2.1. Equivalent admittance at the probe aperture: A general formulation for an open-ended coaxial transmission line terminated to a layered medium is proposed in [17]. The main assumptions of this model are (i) operating only in the transverse electric and magnetic field (TEM) mode and (ii) infinite flange for the coaxial probe. Fig. 1 shows a cross-section structure of the system where inner and outer diameters of the coaxial probe are $2a$ and $2b$, respectively. The normalised aperture admittance at the coaxial probe (with respect to the characteristic admittance of the coaxial line, i.e. Y_0) can be calculated using continuity of the power flow across the aperture as follows

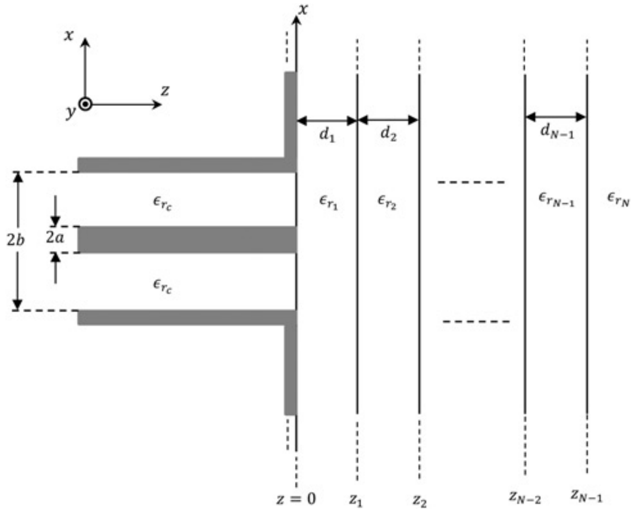

Fig. 1 *Cross-sections of coaxial line radiating into layered media*

$$\frac{Y_{\rm an}}{Y_0} = \frac{\varepsilon_{\rm r_1}}{\sqrt{\varepsilon_{\rm r_c}}\ln(b/a)}\int_0^\infty \frac{[J_0(k_0\zeta b) - J_0(k_0\zeta a)]^2}{\zeta} F(\zeta)\,{\rm d}\zeta \qquad (1)$$

where $Y_{\rm an}$ is the analytically calculated admittance, $\varepsilon_{\rm r_c}$ and $\varepsilon_{\rm r_1}$ are the relative permittivity of the dielectric material of the probe and the first layer, respectively, J_0 is the zero-order Bessel function of the first kind, k_0 is the free-space wave number and $F(\zeta)$ is given by

$$F(\zeta) = \frac{1}{\sqrt{\varepsilon_{\rm r_1} - \zeta^2}}\left(\frac{1+\rho_1}{1-\rho_1}\right) \qquad (2)$$

in which

$$\rho_i = \frac{1 - k_i\beta_{i+1}}{1 + k_i\beta_{i+1}}{\rm e}^{-{\rm j}2k_0 z_i\sqrt{\varepsilon_{\rm r_i} - \zeta^2}}; \quad i = 1, 2, \ldots, N-1 \qquad (3)$$

and

$$\begin{cases} k_i = \dfrac{\varepsilon_{\rm r_i}}{\varepsilon_{\rm r_{i+1}}}\dfrac{\sqrt{\varepsilon_{\rm r_{i+1}} - \zeta^2}}{\sqrt{\varepsilon_{\rm r_i} - \zeta^2}} \\ \beta_{i+1} = \dfrac{1 - \rho_{i+1}{\rm e}^{{\rm j}2k_0 z_i\sqrt{\varepsilon_{\rm r_{i+1}} - \zeta^2}}}{1 + \rho_{i+1}{\rm e}^{{\rm j}2k_0 z_i\sqrt{\varepsilon_{\rm r_{i+1}} - \zeta^2}}} \\ z_i = \sum_{j=1}^{i} d_j \end{cases} \qquad (4)$$

where $\varepsilon_{\rm r_i} = \varepsilon'_{\rm r_i} - j\varepsilon''_{\rm r_i}$ and d_i are the complex permittivity and the thickness of the ith layer, respectively.

2.2. Estimation of the effective permittivity: The effective permittivity of a multi-layer medium is defined as the permittivity of a homogeneous and semi-infinite material which results the same admittance as the multi-layer medium. By facing a coaxial probe to a homogeneous medium, we obtain the aperture admittance as a function of medium permittivity. The inverse of this function will then be used to estimate the effective permittivity from the calculated admittance of a multi-layer medium.

Many models have been presented by researchers to analyse open-ended coaxial probes terminated by semi-infinite homogeneous materials such as capacitive model, radiation model and full-wave simulation model [20]. Among these models, we use the radiation model due to the operating frequency and the probe dimensions [21, 18]. In radiation modelling, the probe is considered as a radiation source. In the stationary condition, the normalised aperture admittance can be written as follows

$$\frac{Y}{Y_0} = j\frac{k^2}{\pi k_{r_c}\ln(b/a)}\int_a^b\int_a^b\int_0^\pi \frac{{\rm e}^{-{\rm j}k_r}}{r}\cos\phi'\,{\rm d}\phi'\,{\rm d}\rho'\,{\rm d}\rho \qquad (5)$$

where

$$\begin{cases} k = \omega\sqrt{\mu_0\varepsilon_0\varepsilon} \\ k_{r_c} = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_{r_c}} \\ r = \sqrt{\rho^2 + \rho'^2 - 2\rho\rho'\cos\phi'} \end{cases} \qquad (6)$$

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in which ε_0 and μ_0 are the permittivity and permeability of vacuum, respectively, and ω is the angular frequency of the EM signal.

When the coaxial opening is electrically very small, (5) can be approximated by the first few terms of the series expansion for the exponential term. By considering the first four terms, the quasi-static approximation can be written as follows

$$\frac{Y_{\text{hom}}}{Y_0} = K_1 + K_2\varepsilon + K_3\varepsilon^2 + K_4\varepsilon^{5/2} \quad (7)$$

where Y_{hom} is the admittance of homogeneous medium, K_1–K_4 are generally complex factors depending on the probe geometrical dimensions. To determine these factors, one can use the closed-form equations or (at least) four media with known permittivities to calibrate.

Now, given the admittance of a multi-layer medium as (1), and the admittance of a homogeneous medium as (7), the effective permittivity of the multi-layer medium is calculated as follows

$$\varepsilon_{\text{e}} = \arg\min\left(\frac{Y_{\text{an}}}{Y_0} - K_1 + K_2\varepsilon_{\text{e}} + K_3\varepsilon_{\text{e}}^2 + K_4\varepsilon_{\text{e}}^{5/2}\right)^2 \quad (8)$$

Equation (8) shows the model of coaxial probe where the output is effective permittivity. In the case that we intend to estimate the thickness of fat layer from the measured permittivity, the equation would be as follows:

$$l_{\text{f}} = \arg\min\left(\frac{Y_{\text{an}}}{Y_0} - K_1 + K_2\varepsilon_{\text{m}} + K_3\varepsilon_{\text{m}}^2 + K_4\varepsilon_{\text{m}}^{5/2}\right)^2 \quad (9)$$

where ε_{m} is the measured permittivity and l_{f} is the thickness of fat layer.

3. Numerical simulation by FDTD analysis: Several assumptions of the analytical model such as TEM field, infinity of the flange and semi-infinity of the last dielectric layer make the validation of this model necessary. In this section, we introduce a more realistic model of the system under study using FDTD analysis. Fig. 2 shows the 3D structure of the probe and the outer layers of the abdominal wall. Through the simulation, only the thickness of the fat layer and the diameter of the probe vary while the other dimensions, e.g. the thickness of skin and muscle layers are set to the nominal values.

In the numerical method, the reflection coefficient is calculated from wave impedance which is itself a function of electric and magnetic fields. Given the electric and magnetic fields at an arbitrary point in the multi-layer medium as $E(\rho, \phi, z)$ and $H(\rho, \phi, z)$, the wave impedance in this point is defined as follows [22]

$$\eta(\rho, \phi, z) = \frac{E(\rho, \phi, z)}{H(\rho, \phi, z)} \quad (10)$$

Let the coordinate origin be the centre of the probe tip and given the symmetry of the system, the wave impedance will be only a function of z; i.e. $\eta(\rho, \phi, z) = \eta(z)$. Furthermore, by assuming TEM mode, the electric and magnetic fields inside the dielectric material of the probe will be formed of radial and azimuthal components, respectively. Hence, (10) at the departure of the probe can be simplified as

$$\eta(z = 0) = \frac{E_\rho(z = 0)}{H_\phi(z = 0)} \quad (11)$$

Finally, the reflected coefficient at the departure of the probe can be written as

$$\Gamma_n = \frac{\eta - \eta_c}{\eta + \eta_c} \quad (12)$$

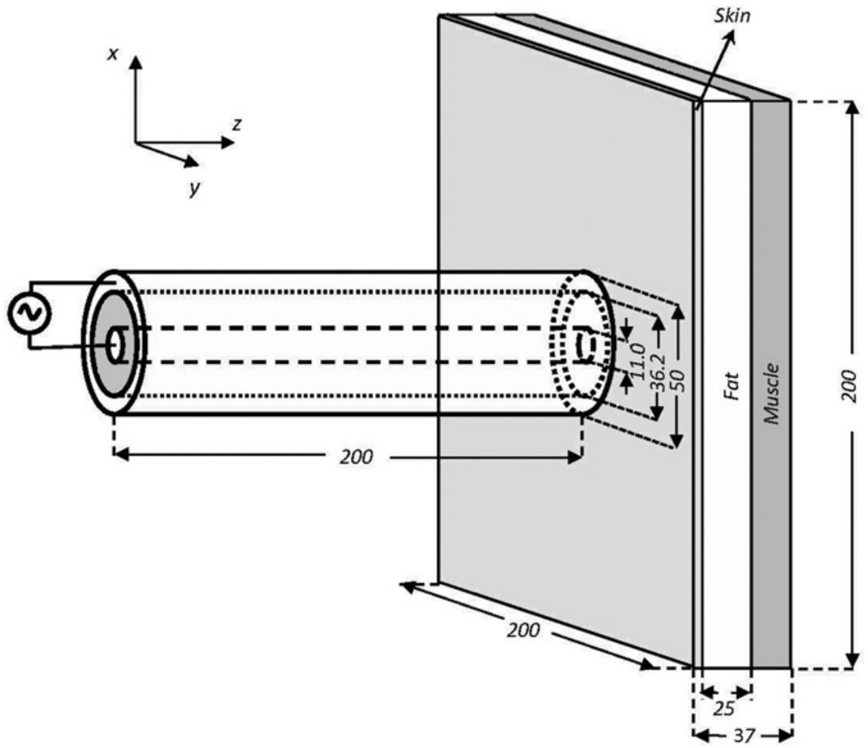

Fig. 2 *FDTD simulation of the coaxial probe (all dimensions are in mm)*

in which η_c is the wave impedance of the probe dielectric

$$\eta_c = \frac{\eta_0}{\sqrt{\varepsilon_{r_c}}} \tag{13}$$

where η_0 is the characteristic impedance of the vacuum.

To validate the assumption of TEM mode at the probe aperture, the system of Fig. 2 with the given parameters is simulated. Fig. 3 shows the measured electric and magnetic fields components in a sector inside the probe with 1 mm distance from the probe tip ($z = -1$ mm). As seen, ρ and z components of the magnetic field and the ϕ component of the electric field are almost zero while the z component of the electric field is not negligible. This is due to the existing higher order modes of the electric field near the aperture [23]. Fig. 4 shows the electric and magnetic components in the probe at $z = -100$ mm. It can be observed that the z component of the electric field is also almost zero and the propagation of the EM wave can be considered as TEM-mode in the new sector.

Since the reflection coefficient is measured at the input of the coaxial probe, the transverse EM field is expected at the measuring point. Reflection coefficient at the probe aperture can be calculated using the following equation where z represents any point along the probe

$$\Gamma_n(0^-) = \Gamma_n(z)e^{-2jkz}; \quad z < 0 \tag{14}$$

Now, the numerically calculated value for aperture admittance (Y_{num}) is obtained from the reflection coefficient as follows

$$\frac{Y_{\text{num}}}{Y_0} = \frac{1 - \Gamma_n(0^-)}{1 + \Gamma_n(0^-)} \tag{15}$$

4. Simulation results: Through the simulations, thickness of the fat layer, diameter of the probe and the distance of the probe tip to the skin will be variable. The dielectric material of the probe is Teflon with $\varepsilon_{r_c} = 2.07$ and the ratio of b/a is assumed to be constant in all simulations ($b/a = 3.3$). Given this set-up, the characteristic impedance of the coaxial line will be almost 50 Ω. The angular frequency of the radio frequency (RF) wave is selected 434 MHz which is the operating frequency of capsule endoscopy in the industrial, scientific and medical (ISM) radio band. The parameters of (7) have been tuned using ten different materials with known permittivities.

4.1. Validation of analytical model: Infinity of the flange, TEM fields (TEM mode) and the infinite thickness of the last dielectric layer are the main assumptions of the analytical model. Given diameter of the probe compared with the abdominal wall surface (Fig. 2), and enough distance between measuring point and the probe tip, the first two assumptions do not have significant impact. We will also show that the third assumption does not effectively decrease the accuracy of the model. This is due to power attenuation of the signal propagating through the muscle layer, so that the reflection of the back interface of the muscle can be neglected. The validation criteria for the accuracy of the analytical model are the difference between aperture impedance of the analytical and the numerical models ((1) and (15), respectively).

Simulation results of analytical model for 50 different conditions and comparing the results with numerical model show the error of 0.87 and 2.84% in the amplitude and the phase of the reflection coefficient, respectively. Considering this error as an acceptable error for the analytical model, the rest of the simulations will be performed using this model.

4.2. Effect of the probe size: The penetration depth of the EM signal is directly related to the probe size (diameter) [24]. Since the

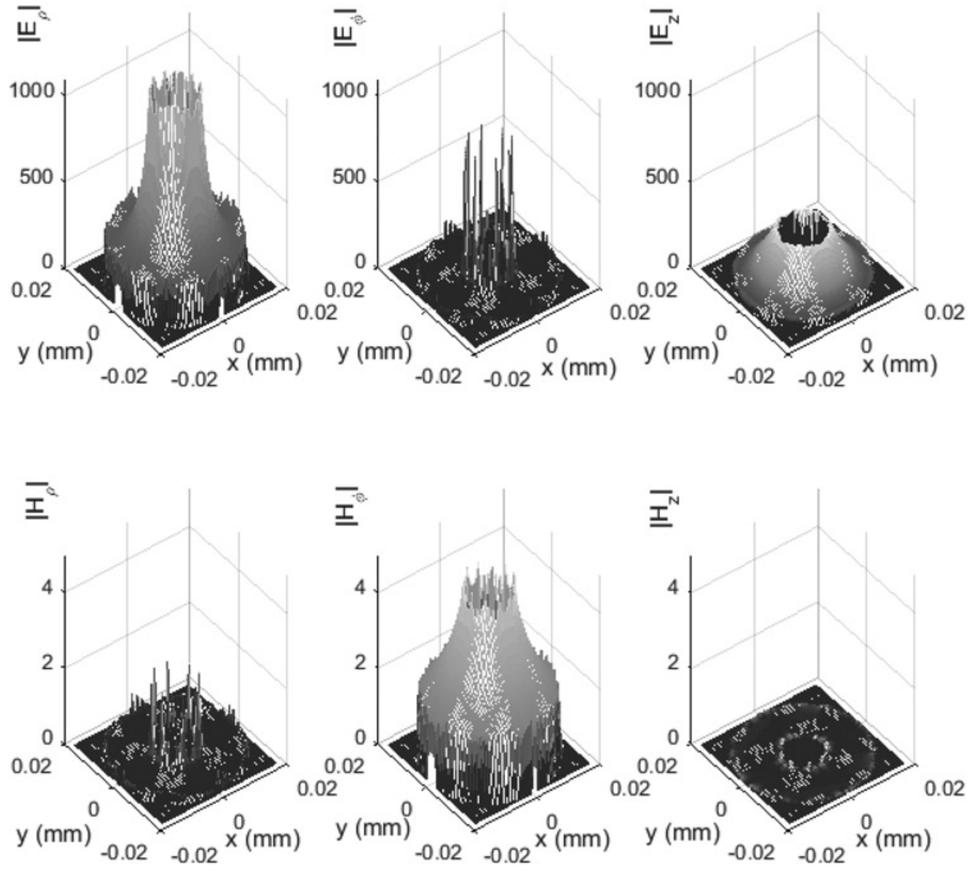

Fig. 3 *Electric and magnetic fields in 1 mm distance from the interface*

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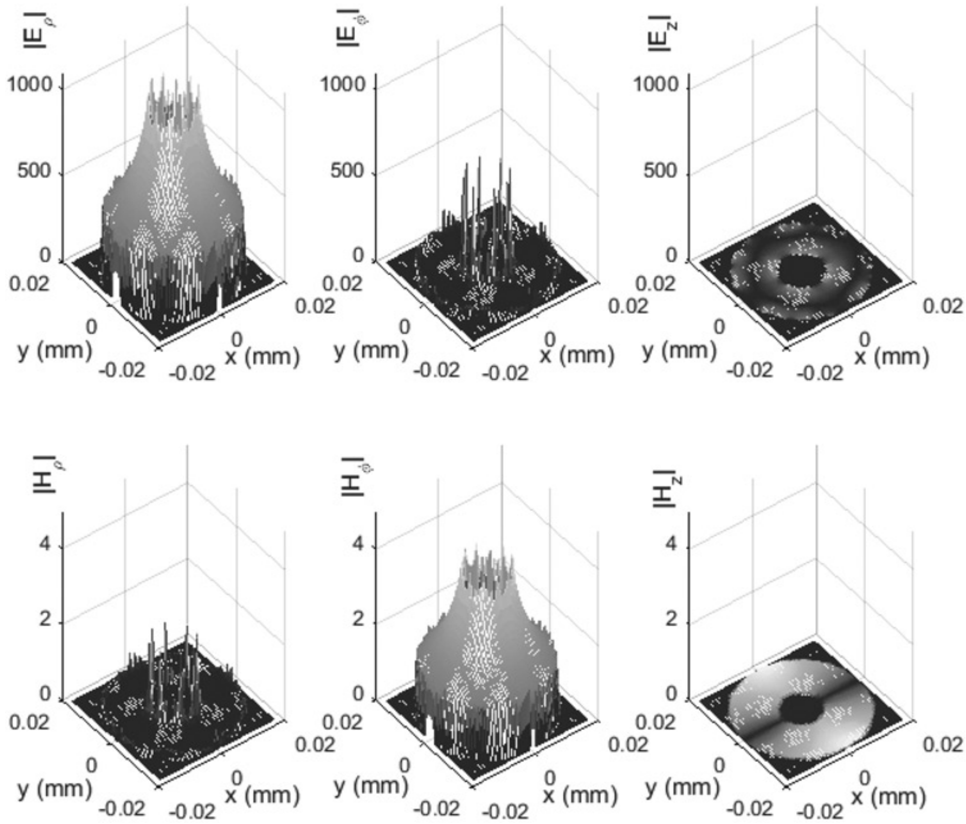

Fig. 4 *Electric and magnetic fields in 100 mm distance from the interface*

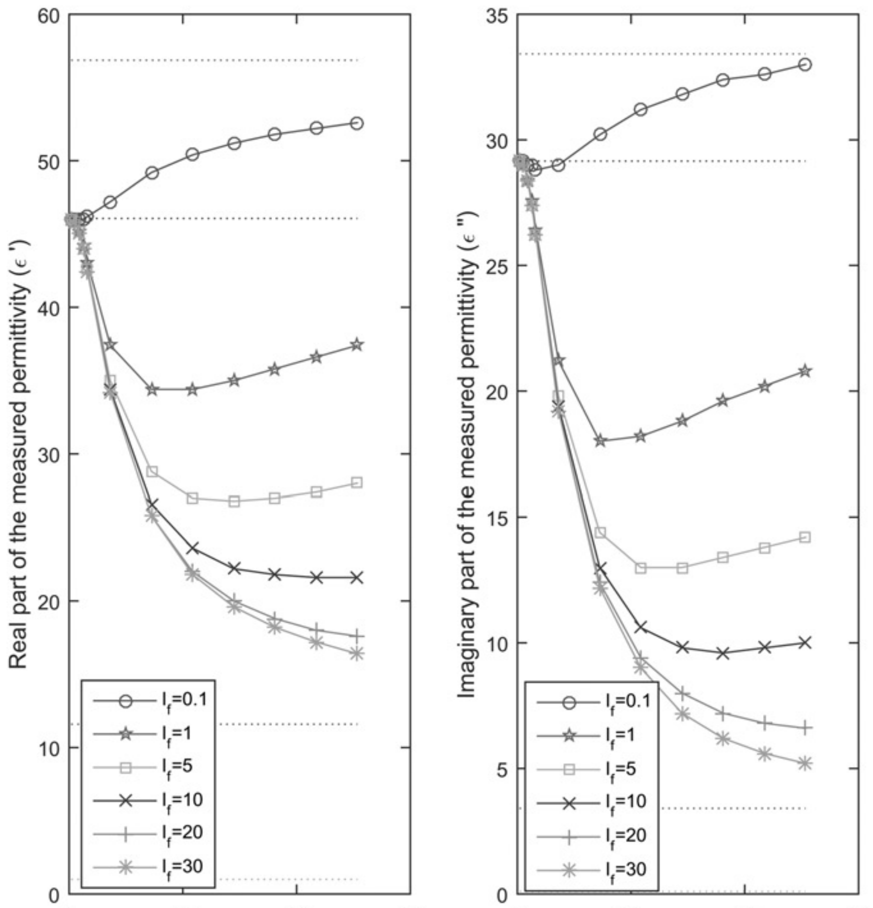

Fig. 5 *Effect of the probe size on the measured permittivity*

Table 1 Statistics of the measured permittivity for variation of the fat layer thickness and different probe sizes

Mean value of the fat layer thickness, mm	$b = 10$ mm		$b = 20$ mm	
	6σ of ε'_e	6σ of ε''_e	6σ of ε'_e	6σ of ε''_e
5	2.45	1.4	4.7	3.05
10	0.85	0.5	2.5	1.75
15	0.3	0.25	1.35	1.1
20	0.15	0.15	0.8	0.75
25	0.1	0.1	0.45	0.45

absorption and reflection coefficient of fat are much less than those of skin and muscle, a gradual increase in the probe size results in a valley-shape behaviour for the measured permittivity. For a very small probe, the penetration depth is very limited and the measured reflection is mainly related to the skin layer. By increasing the probe diameter, the penetration depth also increases and the fat layer has some influence on the measurements. Since the permittivity of fat is less than skin, this effect decreases the measured permittivity. Further increase in the diameter of probe results in the increase in the penetration depth and therefore reaching to the muscle layer and the behaviour of the measured permittivity will be gradually incremental. Fig. 5 shows the measured permittivity versus the probe diameter for different values of fat layer thickness. The horizontal dashed lines in this figure indicate the nominal permittivity of air, skin, fat and muscle. As it can be observed, the larger the size of the probe, the higher the sensitivity of the measured permittivity to the fat layer thickness. Therefore, the accuracy of the thickness estimation of the fat layer can be improved by increasing the probe size. On the other hand, for a fixed size probe, the thinner the fat layer, the more the variation of the measured permittivity. Therefore, the accuracy of the estimation is lower for thicker fat layers.

In fact, estimation of the fat thickness is done by measuring the reflected signal from the muscle layer. The transmitted RF signal by the probe is attenuated while passing through the fat layer, where the attenuation depends on the thickness of fat layer. For thicker fat layers, the penetrated signal through the fat layer and hence the reflected signal from the muscle layer would be weaker. Hence, the sensitivity of the probe will be lower in this case. Increasing the probe size could be a solution to increase the penetration depth and amplify the penetrated signal through the fat layer. The increment in probe size is, however, constrained by the area of MUT which should be significantly larger than that of the probe to fulfil the assumption of semi-infiniteness. Given the limited area of the abdomen, the probe size should be significantly smaller than the surface area of the abdomen.

To have a more detailed investigation of the estimation accuracy, statistical analysis of the simulation results are performed. For this purpose, two different sizes for the probe $b = 10$ mm and $b = 20$ mm, and five different values for the nominal thickness of the fat layer ($l_f = 5$, 10, 15, 20 and 25 mm) are considered. For every simulation, we assume Gaussian distribution over the thickness of the fat layer with mean and standard deviations equal to the nominal values and 10% of the nominal value of the layer thickness, respectively. The simulations are performed 1000 times using Monte Carlo method and the standard deviation (σ) of the measured permittivities are listed in Table 1. A bigger value for the σ of the measured permittivity means higher sensitivity to the variation and hence more accuracy of the estimation. The sensitivity for the thin layers of fat is acceptable, however, for large values of fat layer

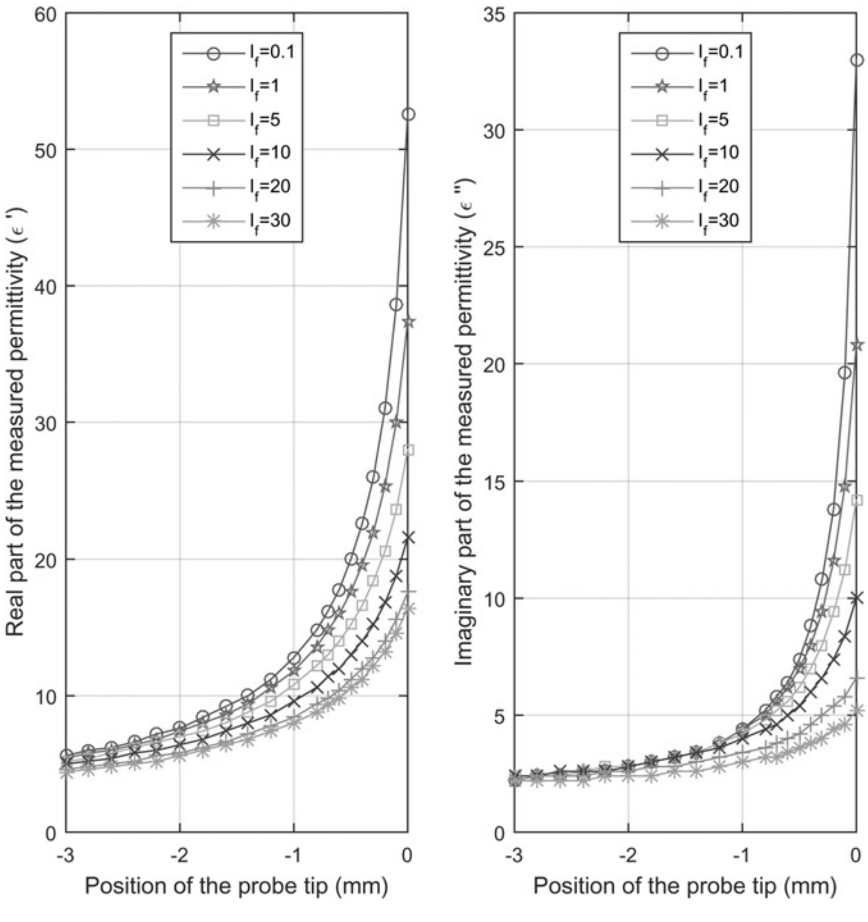

Fig. 6 *Effect of the air gap on the measured permittivity*

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thickness, and the probe with ∼40 mm diameter has a limited accuracy.

4.3. Effect of the air gap: Given that the aperture admittance is a complex value while the thickness of fat layer is a real number, every measurement determines an overdetermined system of equations, as there are two equations and one unknown. Therefore, one can add another parameter of the model (e.g. skin layer thickness) to the unknowns. However, to consider more parameters of the system as unknowns (e.g. the uncertainty of complex permittivity of one or more layers), two solutions are proposed: (i) using several probes with different sizes or (ii) using one probe in different locations relative to the body surface. To use the second solution, one can move the probe and measure the permittivity in different distances between the probe tip and the body skin. Given this distance, a layer air with known thickness is applied to the model. Fig. 6 shows the effect of air gap thickness on the measured permittivity. As it can be observed, only in very short distances between the probe tip and the body skin, the sensitivity of measured permittivity is acceptable and by increasing this distance, the sensitivity is decreased significantly.

5. Discussion and concluding remarks: In this Letter, we presented a novel approach to estimate the thickness of subcutaneous fat layer using coaxial probe. The method is based on the measurements of the effective permittivity of the abdominal wall. This method is non-invasive, simple and computationally inexpensive. The simulations are performed using an analytical multi-layer model and validated using the numerical FDTD simulation. We showed that increasing the size of the probe has a direct positive impact on the accuracy of the estimation of the thickness of the fat layer. Statistical analysis confirmed that increasing the thickness of fat layer decrease the estimation accuracy.

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