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PAPER

Capsule Antenna Design based on Transmission Factor through the Human Body

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SUMMARY To design antennas for ingestible capsule endoscope systems, the transmission factors of dipole and loop antennas placed in the torso-shaped phantom filled with deionized water or human body equivalent liquid (HBEL) are investigated by numerical and experimental study. The S-parameter method is used to evaluate transmission characteristics through a torso-shaped phantom in a broadband frequency range. Good agreement of S-parameters between measured results and numerical analysis is observed and the transmission factors for both cases are obtained. Comparison of the transmission factors between HBEL and deionized water is presented to explain the relation between conductivity and the transmission characteristics. Two types of antennas, dipole antenna and loop antenna are compared. In the case of a dipole antenna placed in deionized water, it is observed that the transmission factor decreases as conductivity increases. On the other hand, there is a local maximum in the transmission factor at 675 MHz in the case of HBEL. This phenomenon is not observed in the case of a loop antenna. The transmission factor of capsule dipole antenna and capsule loop antenna are compared and the guideline in designing capsule antennas by using transmission factor is also proposed.
key words: *Capsule endoscope, conjugate matching condition, transmission factor, dipole antenna, loop antenna*

1. Introduction

Ingestible capsule endoscope system has gained popularity in health-care applications [1-3]. The capsule endoscope system uses a wireless transceiver to obtain medical images of the inside of the human body [1]. High-efficiency antennas for capsule endoscope system have been studied by many researchers [4-11]. Generally, a capsule has a maximum length of 20 mm and a maximum diameter of 10 mm [1], and it is considered that the transmitting power of antennas is extremely low caused by its physical size. The size of the antenna decides the operating frequency. Furthermore, the absorption of electromagnetic waves by the internal organs is quite large caused by high conductivity of the internal organs with frequency dependent characteristics.

Selection of antenna type such as dipole antenna or loop antenna, is important to decrease propagation loss between the capsule antenna and the antenna outside of the human body. In previous studies, several kinds of antennas were proposed for implantable applications [6-10]. Operating frequency of antennas is different such as 400-500 MHz in [6], the center frequency of 1.4 GHz in [8], or with the UWB band in [10]. Finding a suitable frequency band for high efficiency transmission for the capsule endoscope system is quite important.

Estimation of the RF-link budget is essential in the capsule endoscope communication systems. Path loss through the human body was presented by several different expressions [11-16]. In [13], the electric field attenuation along the coordinate axes was used to express path loss. The receiving antenna was considered in [14] and $|S_{21}|$ was used to express the path loss. In [15], the difference of $|S_{21}|$ with and without the human body was used for the definition of transmission loss.

In our previous research [17], a dipole antenna placed in a phantom filled with lossy liquid was studied. The impedance matching was obtained at a frequency, also a large value of $|S_{21}|$ was observed. The experimental results are agree with the calculated results, however, the study concerning the path loss was not carried out. In [18], the path loss has been studied in an in-homogeneous model and only the numerical results were presented, however, it is difficult to perform the experiment in an in-homogeneous real human body model.

In this research, a pair of dipole and a pair of loop antennas were placed inside and outside a torso-shaped phantom used in [17], respectively, and the transmission factor was evaluated by both the numerical and the experimental method. The FDTD (Finite-Difference Time-Domain) analysis with considering frequency dependent dielectric permittivity was used as the numerical analysis.

The transmission factor is used as an indicator of propagation loss. The transmission factor is the relative maximum received power under the condition that the complex-conjugate matching conditions are satisfied at both transmitting and receiving ports. The transmission factors of a dipole and a loop antenna immersed in two kinds of homogeneous liquids are studied to select the suitable antenna and to obtain the suitable operating frequency. The guideline in designing capsule antennas by using transmission factor is proposed. Also the transmission factors of capsule dipole antenna and capsule loop antenna are studied including the effect of surrounding capsule.

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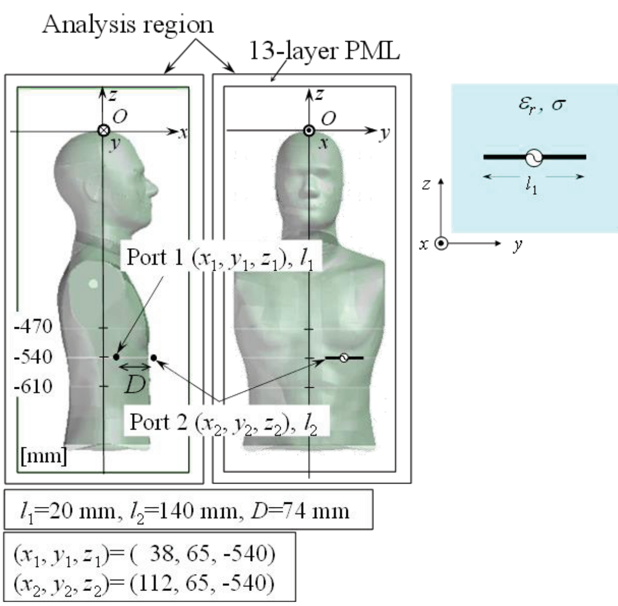
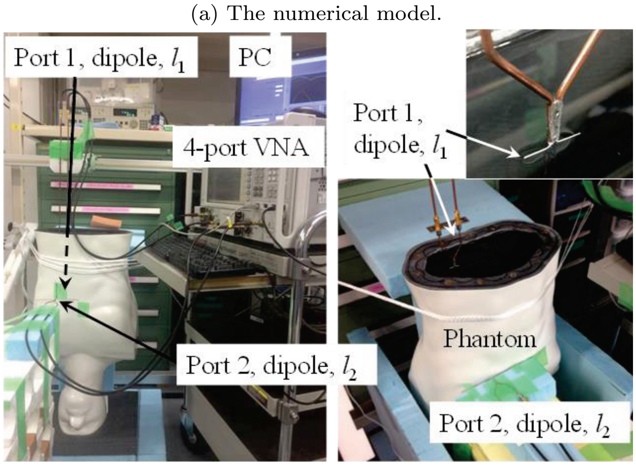
The manuscript is organized as follows: The analysis model and experimental setup are shown in Section 2. In Section 3, the definition of transmission factor is described and studied. The guideline in designing capsule antenna is proposed in Section 4. Finally, results and observations are summarized in Section 5.



(a) The numerical model.

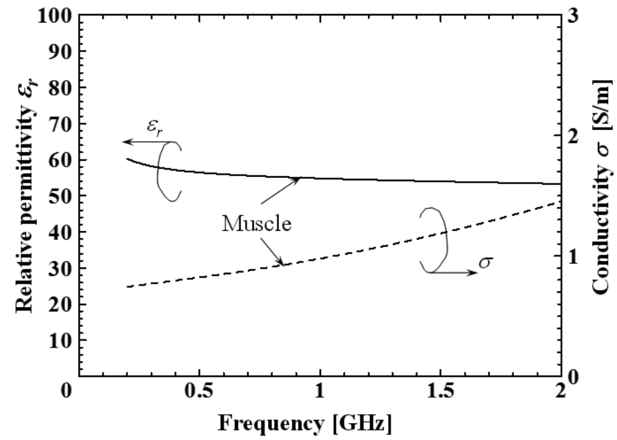


(b) The experimental setup.

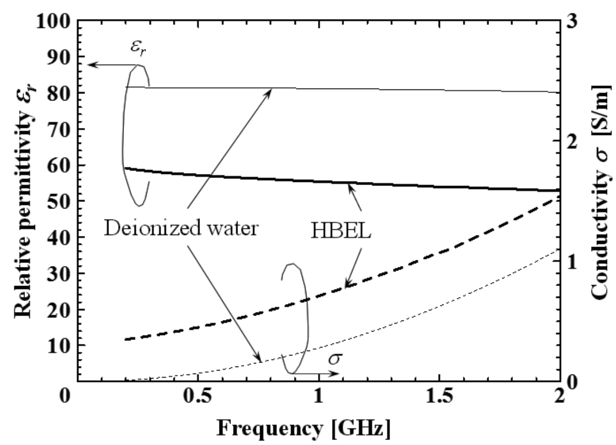
Fig. 1 Human torso-shaped model with dipole antennas.

2. Analysis model and experimental setup

In this research, a commercial human torso-shaped phantom developed by SPEAG was used as the container of liquid. The shell of phantom is made of fiberglass (ϵ_r=3.5) and the thickness is around 2 mm [19]. Figure 1 shows the numerical model and the experimental setup. A dipole antenna with length l1 was placed inside the torso phantom at the position indicated as



(a) Muscle.



(b) Deionized water and HBEL.

Fig. 2 Relative permittivity and conductivity.

Port 1 (x_1, y_1, z_1), which is selected as a typical position of the stomach in the human body. And a dipole antenna with length l_2 was placed outside of the torso phantom as Port 2. The distance between the antennas was set to D=74 mm.

The in-homogeneous real human body was studied numerically in [17], a homogeneous material with relative permittivity and conductivity similar to the muscle human body tissue, was used as a human body equivalent material liquid (HBEL) [18]. In order to study the effect of conductivity on the propagation loss, deionized water was also evaluated. Figure 2 shows the measurement results of relative permittivity and conductivity of the deionized water and HBEL obtained by using the coaxial probe DAK 1.2 provided by SPEAG [19]. In the measurement, the torso-shaped phantom was filled with deionized water or HBEL with a temperature of 18 °C. It is found that

a) In the frequency range of 200 MHz to 2 GHz,there is no particularly difference between the measured value of HBEL and the measured data of human body tissues provided by S. Gabriel [20].

b) The conductivity of deionized water is lower than that of HBEL in the frequency range of 200 MHz to 2 GHz.

c) The conductivity at the lower frequency of around 200 MHz is almost zero in the case of deionized water and is finite values in the case of HBEL.

In the FDTD analysis, the number of cells is 202×304×462, the Gaussian differential pulse is used as an excitation. Subgridding technique was used and the cell sizes are Δx=Δy=Δz=2 mm for the human torso-shaped phantom and Δx=Δy=Δz=1 mm for the antennas. 13-layer PML was used as an absorbing boundary condition. To simplify the investigation, the ohmic loss of the antennas were ignored and the material of antennas were considered as perfect electric conductors.

In the experiment, S-parameters of differential mode S_{dd11}, S_{dd22} and S_{dd21} [22] were measured by using four-port Vector Network Analyzer (Keysight N5224A) in order to compare with the numerical results in the broadband frequency range. In this paper, these differential mode S-parameters were indicated as S_{11}, S_{22} and S_{21}.

3. Transmission factor through human body phantom

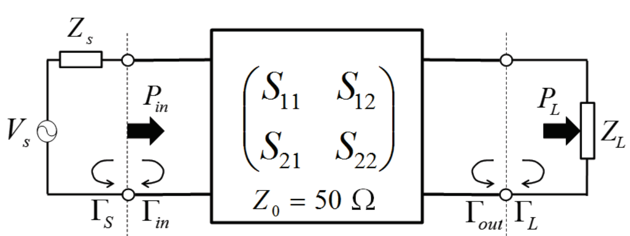


Fig. 3 Two-port equivalent circuit.

Two-port network equivalent circuit is shown in Figure 3 [25]. Transmitting antenna is connected to a source with an internal impedance of Z_S, while receiving antenna is loaded with an internal impedance of Z_L. P_L is the power delivered to the load Z_L, P_{in} is the input power, P_{inc} is the incident power, Γ_S and Γ_L are the reflection coefficients looking toward the source Z_S and the load Z_L, respectively, and Γ_{in} and Γ_{out} are the reflection coefficients looking toward Port 1 and Port 2. In this equivalent circuit, there is a relation as

$$\frac{P_L}{P_{inc}} = \frac{1-|\Gamma_S|^2}{|1-\Gamma_S\Gamma_{in}|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}. \tag{1}$$

where

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0}, \Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{2}$$

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}, \Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}.$$

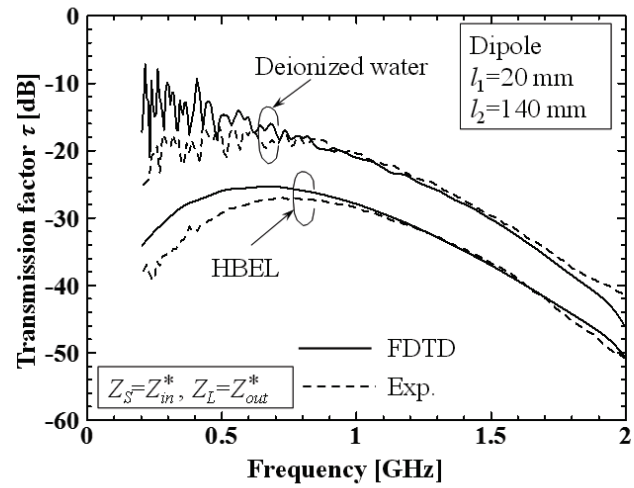
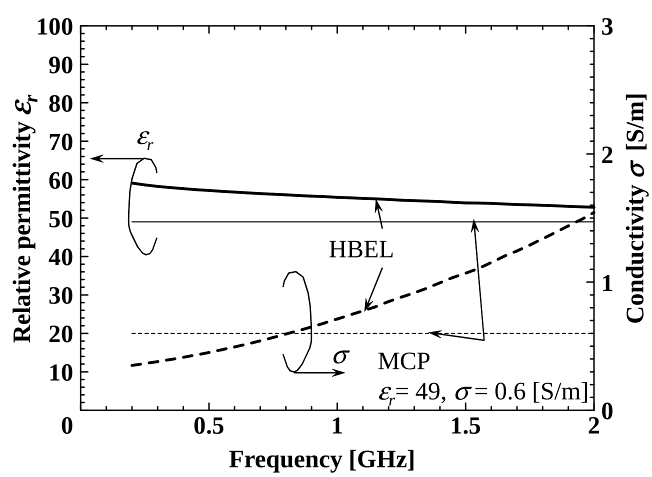


Fig. 4 Transmission factor τ of dipole antenna through torso-shaped phantom.



(a) Relative permittivity and conductivity of material with constant permittivity (MCP) and HBEL.

(3)

If antennas are perfectly matched to the loads with the complex- conjugate impedances at both Port 1 and Port 2 as

$$\Gamma_S = \Gamma_{in}^*, \Gamma_L = \Gamma_{out}^* \tag{4}$$

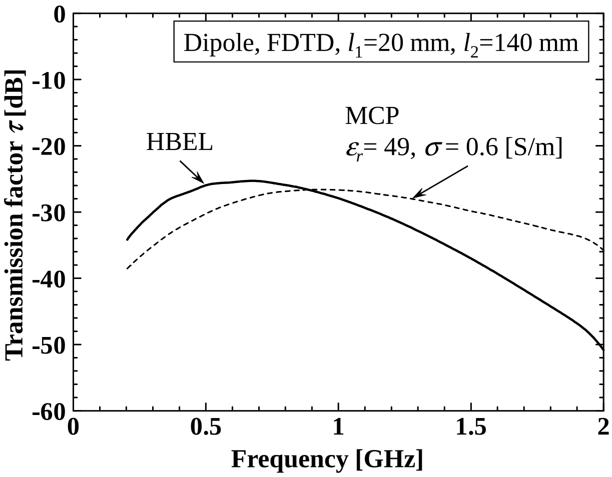
or

$$Z_S = Z_{in}^*, Z_L = Z_{out}^*, \tag{5}$$

, there is no reflection at Port 1, the incident power is equal to the input power

$$P_{in} = P_{inc} \tag{6}$$

and the transmission factor τ is defined by using S-parameters of the circuit as



(b) Calculated transmission factor τ in the case of a dipole antenna immersed in material with constant relative permittivity (MCP) and HBEL.

Fig. 5 Transmission factor τ in the case of a dipole antenna immersed in liquid.

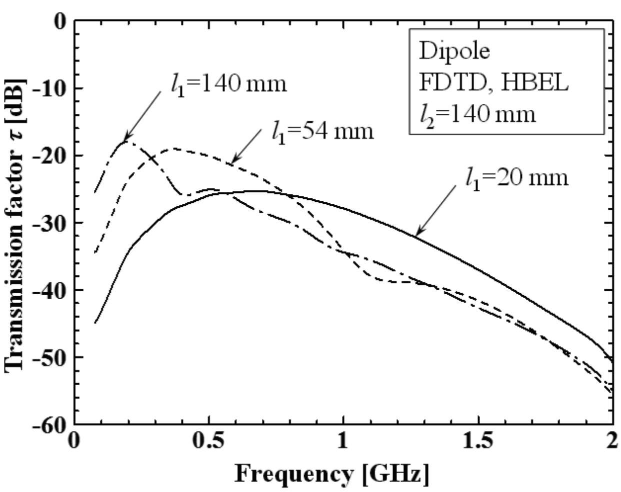
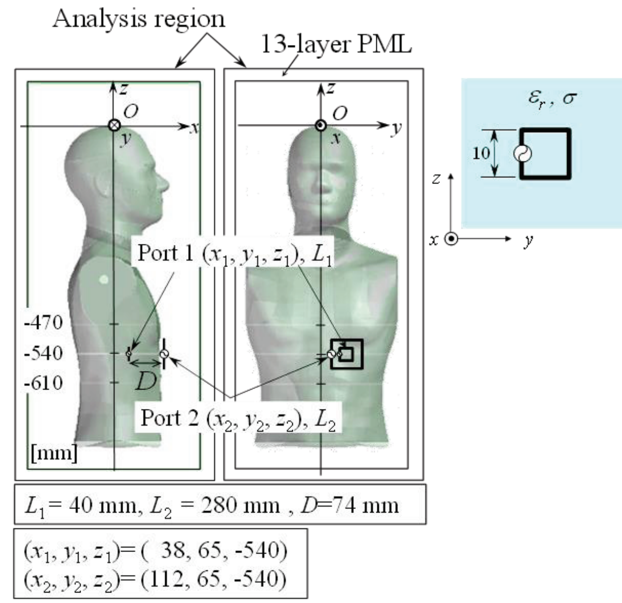


Fig. 6 Calculated transmission factor τ of dipole antenna with different length l_1 immersed in HBEL.

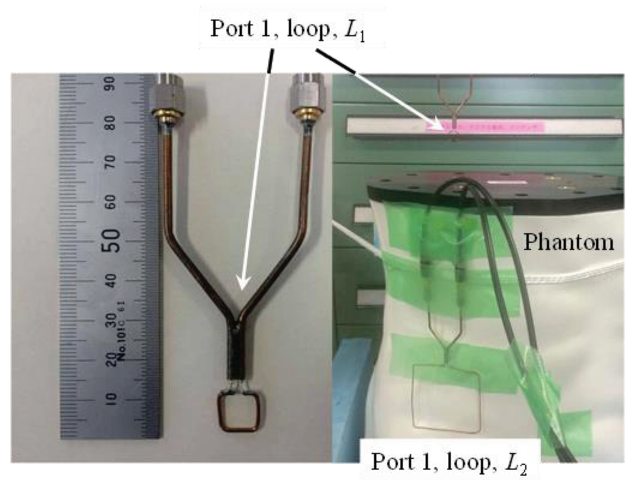
$$\tau = \left.\frac{P_L}{P_{inc}}\right|_{Z_S=Z^*_{in}, Z_L=Z^*_{out}} = \frac{P_L}{P_{in}} = \frac{1}{1-|\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}. \tag{7}$$

In the case when Z_S=Z_L=50 Ω, the transmission factor τ can be written as $|S_{21}|^2$. The transmission factor τ is the relative, maximum received power which excludes the mismatch effects of the antennas and includes the cases when Z_S and Z_L are not equal to 50 Ω. In this research, the transmission factor τ is used as the propagation loss to investigate the transmission characteristics of EM-wave through human body.

Figure 4 shows the transmission factor τ of dipole antenna through a torso-shaped phantom filled with deionized water or HBEL. In the case of dipole antenna placed in deionized water, it is observed that the transmission factor τ decreases as the conductivity increases. In the low frequency range, the conductivity of the deionized water is almost zero and the transmission factor τ is quite large (almost -15 dB) with several vibrations caused by the multiple reflections inside a phantom. On the other hand, in the case of HBEL with higher conductivity compared to the deionized water, a local maximum with level of -25.3 dB is observed at 675 MHz corresponding to the half-wavelength resonant frequency (l_1=$\lambda_g/2$) of the dipole antenna immersed in HBEL. The value of τ at 675 MHz is -28 dB which is 2.7 dB larger than the value at 1 GHz. Differences between experimental values and FDTD results for both in the case of deionized water and HBEL become larger in the low frequency range, which was caused by the dif-



(a) The numerical model.



(b) The experimental setup.

Fig. 7 Human torso-shaped model with loop antennas.

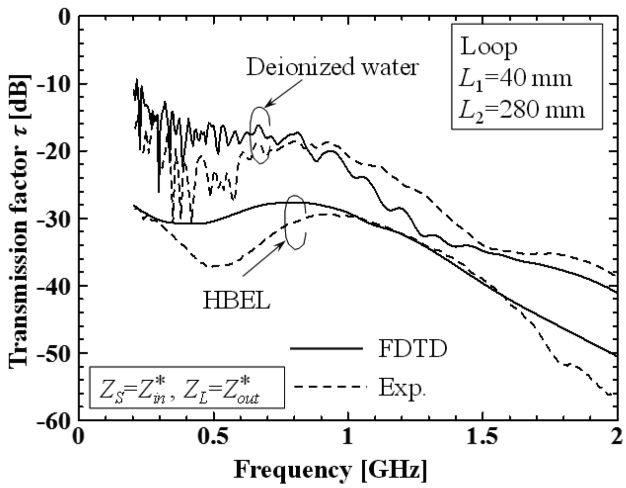


Fig. 8 Transmission factor τ of loop antenna through torso-shaped phantom.

ference between the simulation phantom and the experiment phantom, the setting accuracy of the immersed antenna, and the effect of the conducting jig in the experiment. The transmission factor τ is mainly affected by the geometry of a phantom, distance between antennas and conductivity of the liquid.

To study the relationship between the transmission factor τ and the conductivity of the liquid, an imaginary numerical material with constant permittivity (MCP, ε_r=49, σ=0.6 S/m) was supposed to compare with HBEL, as shown in Figure 5(a). Figure 5(b) shows the calculated transmission factor τ when a dipole antenna is immersed in MCP and is immersed in HBEL. It was observed that the magnitude of transmission factor τ replace with a frequency boundary of 850 MHz which is corresponding to the frequency of conductivity boundary as shown in Figure 5 (a). This phenomenon demonstrates that a higher σ causes a lower τ.

Figure 6 shows the calculated transmission factors τ in HBEL when the length of dipole antenna are l_1=20 mm, 54 mm, and 140 mm, respectively. The maximum value of τ increases as the length of antenna increases. These frequency changes of local maximum are considered as the half-wavelength resonant frequency of the dipole antenna. However, in practical application, the length of capsule antenna is limited to 20 mm, and the maximum value of τ is considered around -25 dB to -30 dB when a capsule antenna is placed in the middle of a human body.

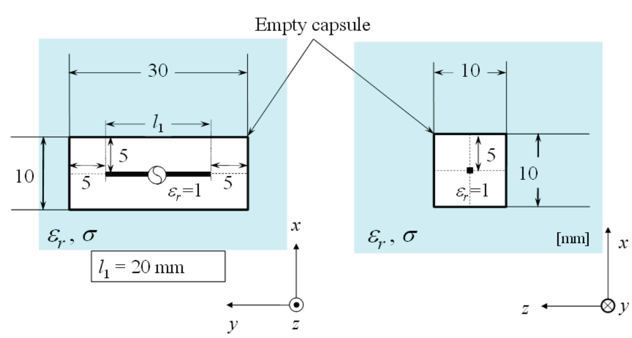
The rectangular loop antenna was also studied to compare with the results of dipole antenna. Figure 7(a) and (b) show the numerical model and experimental setup of a torso-shaped phantom with a pair of loop antennas. A rectangular, 1-turn loop antenna with loop length of L_1=40 mm was immersed in HBEL as Port 1, and a rectangular loop antenna with loop length of L_2=280 mm was placed outside the phantom as Port 2.

Figure 8 shows the transmission factor τ in the case of loop antenna immersed in deionized water and HBEL. A good agreement is obtained between the experiment and the FDTD analysis. It is observed that difference of curves and values of the transmission factor τ are small between the cases of dipole antennas and loop antennas except for the lower frequency range of around 200 MHz.

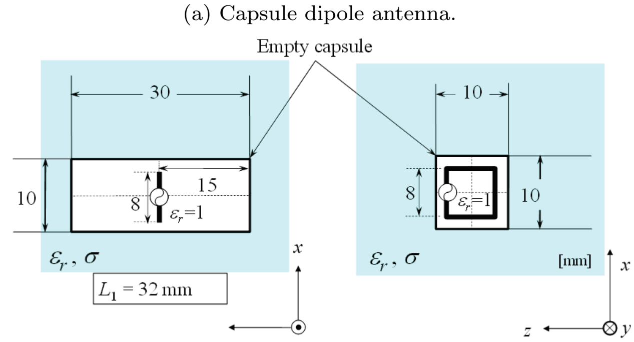
4. Capsule antenna design

In this section, an example of capsule antenna design by using the transmission factor τ is presented. The antennas were enclosed by the rectangular column capsule as shown in Figure 9. Generally, the capsule has chamfered shape. Under the condition that the antenna is placed inside the capsule, the effect of the shape of the capsule can be ignored. The results of the chamfered shape capsule were proposed previously [23], and the results are the same with the rectangular shaped capsule. In this section, the rectangular shaped capsule was used because it is easy to make voxels and save numbers of cells in the FDTD analysis. Dimension of the rectangular column capsules are with length of 30 mm and width of 10 mm. To simplify the investigation, relative permittivity of capsule is set as the air (ε_r=1).

In the case of capsule loop antennas, the antennas and the phantom are with the same structure as shown in Figure 7, except for the presence of a rectangular column capsule. A rectangular loop antenna with a loop

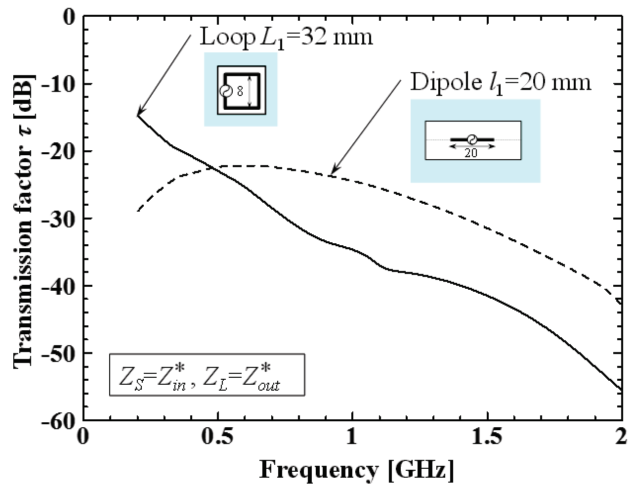


(a) Capsule dipole antenna.

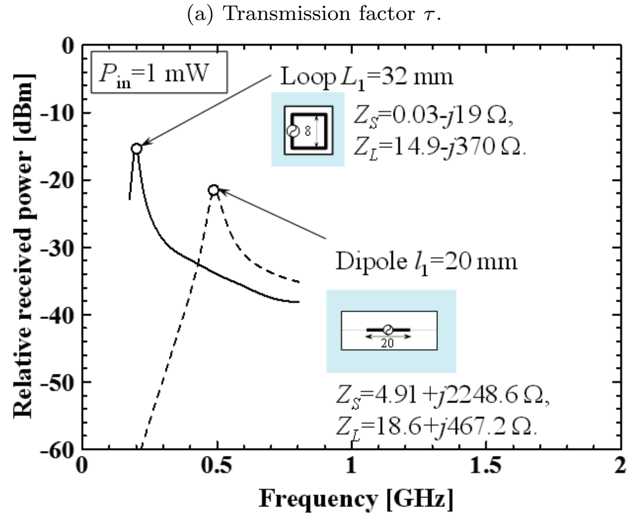


(b) Capsule loop antenna.

Fig. 9 Structure of capsule antennas.



(a) Transmission factor τ.



(b) Relative received power.

Fig. 10 Transmission factors and relative received power of capsule dipole and loop antenna through torso-shaped phantom.

length of L_2=280 mm was placed outside the phantom. A rectangular capsule loop antenna with a loop length of L_1=32 mm was placed in the phantom as shown in Figure 9(b).

Figure 10(a) shows the transmission factor τ, and Figure 10(b) shows the relative received power of capsule dipole antenna and capsule loop antenna through torso-shaped phantom, respectively. In the case of capsule dipole antenna, it is found that there is a local maximum in the transmission factor τ at a frequency, which is also observed in the case without the capsule enclosure. As an example of the internal impedances, Z_S=4.91+j2248.6 Ω and Z_L=18.6+j467.2 Ω can be selected and it can be used as the external matching circuits. It is noted that large value of τ=-21.6 dB at 490 MHz is observed which is 3.7 dB larger than the case shown in Figure 4 at 695 MHz. This increment of the transmission factor τ is considered that the feeding point of dipole antenna is not touched with the lossy liquid by the presence of a capsule enclosure.

In the case of capsule loop antenna, the transmission factor τ is large especially in the low frequency range. Under the conditions Z_S=0.03-j19 Ω and Z_L=14.9-j370 Ω, a large value of τ=-14.7 dB is obtained at the lowest frequency of 200 MHz. This will be caused by the strong magnetic-coupling between two loop antennas in the near-field region, while this phenomenon was not appeared between two dipole antennas. In our previous research, the power-transmission efficiency could approach very high if the two small loop antennas with the same size and the distance was short enough in the air [23]. In capsule antenna applications, because human body is a high electric lossy medium rather than a magnetic lossy medium, the magnetic coupling of two loop antennas increases the transmission factor in the near-filed region in the low frequency range.

5. Conclusion

In this research, EM-wave propagation through a human body phantom was studied in the frequency range 200 MHz to 2 GHz. The transmission characteristics of a dipole antenna and a loop antenna immersed in the torso-shaped phantom filled with deionized water or human body equivalent liquid were investigated by the FDTD analysis and the measurements.

Good agreement between measured and calculated results is observed. The transmission factor τ was used to evaluate the path loss through the human body phantom. It is found that the transmission factor τ decreases as the conductivity increases in the case of dipole antenna placed in deionized water. On the other hand, there is a local maximum in the transmission factor τ at a frequency in the case of HBEL. Also it is found that this phenomenon is not observed in the case of the loop antenna.

The effect of capsule enclosure was discussed by using the transmission factor τ and design of capsule antennas has been performed with several guidelines as follows: the local maximum in the transmission factor around 600 MHz appears when used antennas are dipole type. Lower frequency should be used to obtain large value of the transmission factor τ when used antennas are loop type. In practical use of these guidelines for the application of ingestible capsule endoscope, the results in this study are considered applicable even in the cases when the geometry of capsule antenna becomes complex, because of the fact that the size of capsule antenna is small compared with the effective wavelength in high permittivity organs.

Acknowledgment

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