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Study on the Electromagnetic Field Distribution of an Implantable Antenna for an Intelligent Health Monitoring System

YANG LI, WENQING DUAN, LICHENG YANG, AND XIAONAN ZHAO
Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University, Tianjin 300387, China
College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin 300387, China

Corresponding author: Yang Li (liyang_tongxin@163.com)

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ABSTRACT In this paper, an intelligent health monitoring system based on body-centric wireless communications is studied, and the implantable antenna is investigated. To design the antennas for intelligent health monitoring systems, the electromagnetic near-field distribution of an implantable antenna placed in the alimentary canal of a human body is investigated by a numerical analysis. The electronic field distribution and the transmission factor of an implantable antenna placed in different parts of the human alimentary canal are presented and compared. It is found that the electronic field distribution of the implantable antenna depends on the operating frequency of the antenna and the conductivity distribution of the human body. The transmission characteristics of the electromagnetic wave from the implantable antenna to the outside depending on the frequency, distance, and filling materials of the alimentary canal. The impedance matching of the implantable antenna in different organs is also presented and compared.

INDEX TERMS Intelligent body healthcare management, implantable antenna, near-field distribution, transmission characteristic, impedance matching.

I. INTRODUCTION

Recently, antenna technology and communication technology have become increasingly important in the application of intelligent body healthcare monitoring system. An intelligent body healthcare monitoring system is based on body-centric wireless communications (BCWCs), which mainly include two kinds of systems, wearable monitoring systems and implantable monitoring systems [1]. A sensor or sensor network can be applied with both wearable and implantable monitoring systems, and there have been many previous studies focusing on sensor networks [2]–[10]. The main purpose of a sensor network is to monitor an area, as is performed in target detection, source localization and direction arrival estimation. Through wearable electronic sensors or implantable electronic sensors, we can detect human health indicators such as heart rate, body temperature, blood pressure and so on. In this study, we focus on implantable monitoring systems.

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Implantable monitoring systems have many application scenarios, such as the monitoring of vital signs of bedridden patients in hospitals, the monitoring of human alimentary canal diagnosis and so on. The idea of an implantable capsule was first proposed in 1957 [11], and has been developed rapidly over the last 20 years [12]–[14]. The implantable capsule endoscope uses a wireless transceiver to obtain medical images of the inside of the human body [11]. High efficiency antennas for an implantable capsule endoscope system have been studied by many researchers [15]–[18]. Generally, a capsule has a limitation in its size; with a maximum length of approximately 20 mm and with a maximum width of approximately 10 mm [11], and it is considered that the transmitting power of implantable antennas has a limitation caused by the physical size. Furthermore, the absorption of electromagnetic waves by human body organs is quite large, and the transmitting power from implantable antenna to the outside becomes weak, especially in the high frequency band, because conductivity of the human body increases with increased frequency. Studies on transmission characteristics depending on the frequency, the distance, and the different organs are important to increase the transmission's effect between the implantable antenna and the antenna outside of human body.

In our previous work, homogenous human body phantoms were used in some studies [19], [20], as when a capsule-carried implantable antenna passes through various organs of the alimentary canal, the surrounding environment of the capsule changes from moment to moment, and the absorption of the electromagnetic waves changes continuously. In human body organs with different dielectric permittivities and conductivities, the size of the antenna compared with the wavelength of its operating frequency changes from moment to moment, so it is important to considering an in-homogenous human body phantom with a realistic human alimentary canal. The alimentary canal is a group of organs working together to convert food into energy to feed the entire body, and this canal is made up of the esophagus, stomach, small intestine, large intestines and so on, as shown in Figure 1. The transmission characteristics of an electromagnetic wave through the human body were studied by several researchers for particular organs. For example, in [22], the communication link-budget was discussed from the arm to the outside, and in [23], the transmission characteristics from the small intestine to the outside was investigated. However, few researchers have studied electromagnetic field distribution and transmission characteristics of electromagnetic wave propagation from different parts of the alimentary canal to the outside.

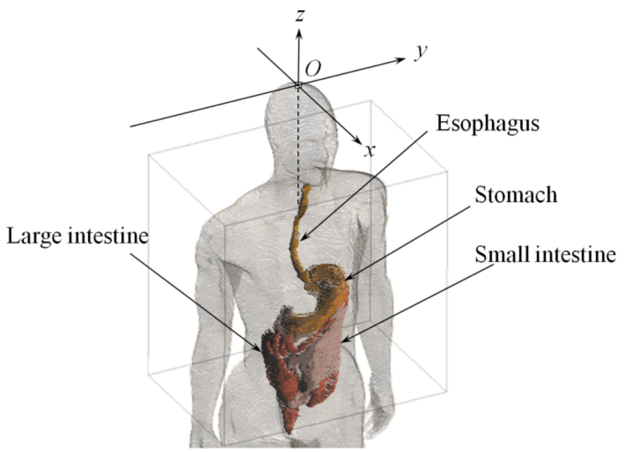

FIGURE 1. Alimentary canal.

In [21], the transmission factor was studied in an in-homogeneous human body phantom, while the electric field distribution was not studied. In this research, the electric field distribution and the transmission factor [24] are studied as indicators of propagation loss to evaluate the electromagnetic wave propagation from different parts of the human alimentary canal to the outside. The electromagnetic simulation results are carried out by using a 3D full-wave electromagnetic and computational life sciences simulation software SEMCAD, which is based on the finite-difference time-domain (FDTD) method.

The remainder of this manuscript is organized as follows: The numerical human body phantom and the analysis model are shown in Section 2. The electric field distribution and the definition of the transmission factor are described in Section 3. The transmission characteristics of the implantable antenna, depending on the frequency, are studied in Section 4. The transmission characteristics depending on the distance are studied in Section 5. The transmission characteristics depending on different organs and impedance matching are investigated in Section 6. Finally, some results and observations are summarized in Section 7.

II. NUMERICAL HUMAN BODY PHANTOM

Computational human phantoms are models of the human body used in computerized analysis. The computational cross section are shown in Figure 2. The origin is set in the head and the lines in the xoz-plane represent the different positions of the alimentary canal used to place the capsule antenna: $z_1 = -400$ mm, $z_2 = -470$ mm, $z_3 = -540$ mm, $z_4 = -610$ mm, and $z_5 = -700$ mm correspond to the position of the esophagus, stomach, and small and large intestines, respectively. The phantom, made with an MRI image with 76 kinds of organs, and the relative permittivity and electrical conductivity of these organs as provided by ITIS (USA) are used. To solve the problem with the FDTD method, the relative permittivity and electrical conductivity of organs can be approximated by the generic equation:

$$\tilde{\varepsilon}(\omega) = \varepsilon_\infty - j\frac{\sigma}{\omega \cdot \varepsilon_0} + \sum_{p=1}^{p} \frac{A_p}{-\omega^2 + B_p \cdot j \cdot \omega + C_p} \tag{1}$$

where ε_∞ is the permittivity for $\omega \rightarrow_{\infty,\varepsilon 0}$ is the vacuum permittivity, σ is the conductivity, and A_p, B_p, C_p represent the coefficients for the generic dispersive model. The color in the

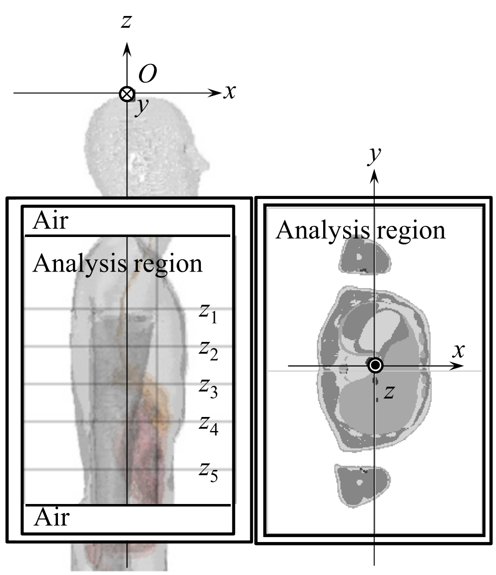

FIGURE 2. Samples of relative permittivity and conductivity of human body organs.Model setup model.

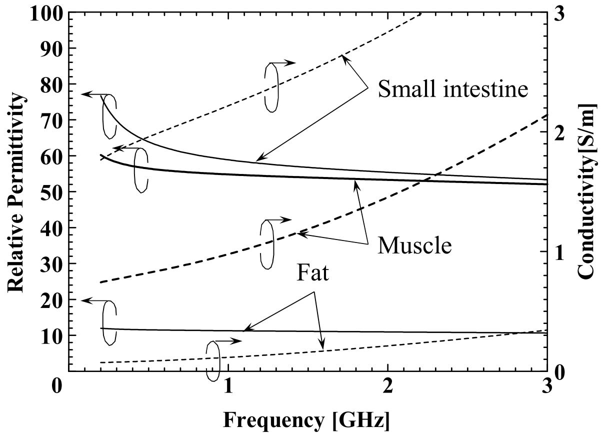

FIGURE 3. Samples of relative permittivity and conductivity of human body organs.

xoy-plane cross section in Figure 2 depends on the conductivity of the human body organs. Figure 3 shows samples of body materials such as: small intestine, muscle and fat [25], [26]. It is considered that it is not necessary to calculate the whole body model, so only the torso of the body (truncated body) is calculated. 13-layer perfectly matched layer (PML) is used and is separated from the calculated body by an air box. In the FDTD analysis, the ohmic loss of the implantable antennas is ignored to simplify the investigation.

The geometry of the cylindrical column capsule is shown in Figure 4. The vacuum capsule is a cylinder with a total length of $l_c = 30$ mm, and two hemispherical shells with a radius $r = 5$ mm at both ends. A simple dipole antenna with a length of $l_1 = 20$ mm is placed inside the capsule, and both the capsule and dipole are placed inside the human body.

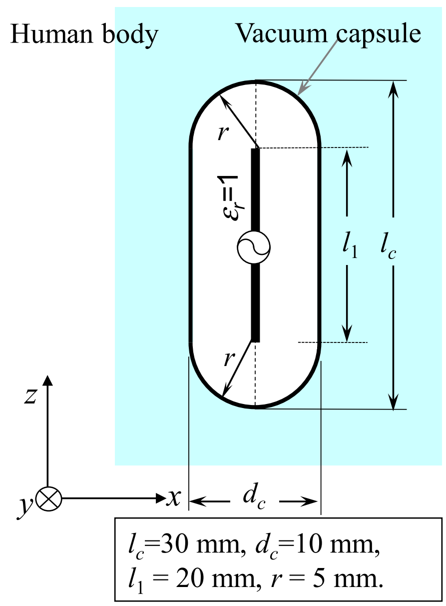

FIGURE 4. Structure of cylindrical capsule and dipole antenna.

III. ELECTRIC FIELD DISTRIBUTION AND TRANSMISSION FACTOR OF AN IMPLANTABLE ANTENNA

The human body conductivity distribution and electric field distribution at 500 MHz are shown in Figure 5. The capsule is placed in the esophagus as an example. Figure 5(a) shows the conductivity distribution and the 2D electric distribution. It is found that the conductivity of the heart is large and the electric field distribution is stronger at the back of the human body than that in the front of the human body. Figure 5(b) shows the 1D electric line distribution. It is shown that the attenuation of the electric field intensity in the front is larger than that in the back. Figure 5(c) shows the 2D electric distribution of E_x, E_y and E_z. Because the dipole is placed vertically, the electric field intensity in the z direction is stronger than that in the x direction and the y direction. The maximum electric field intensity is where the implantable antenna is placed. It is observed that the attenuation of the electric field intensity in front of the human body is greater than that in back of the human body, this finding is because the high conductivity of the heart causes large electromagnetic wave attenuation toward the front.

The transmission factor is used as an indicator in order to evaluate the propagation loss from different parts of the human alimentary canal to the outside. The transmission factor is evaluated under the condition of the complex conjugate matching conditions that are satisfied at both transmitting and receiving ports, which was studied carefully before in [19], [21], and [24]. The optimal internal and load impedance can be calculated for impedance matching. The transmission factor is defined as:

$$\tau = \frac{P_L}{P_{in}} = \frac{1}{1-|\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \quad (2)$$

IV. TRANSMISSION CHARACTERISTICS DEPEND ON FREQUENCY

Because different materials have different relative permittivity and conductivity, it is necessary to consider the effect of the filling materials in the alimentary canal.

Under the conditions that the lumina of the alimentary canal are filled with water and the capsule is placed in the stomach, the transmission factor depends on the frequency, as shown in Figure 6. It is found that the maximum value of the transmission factor is aprroximately −23 dB at 500 MHz. This finding is because the dipole antenna implanted in the stomach is at half-wave resonance frequency at 500 MHz and the radiation efficiency is high. The transmission factor decreases as frequency increases; −30 dB at 700 MHz, −45 dB at 1.25 GHz, and −47 dB at 1.5 GHz. This result is because the conductivity of human tissue increases as frequency increases, resulting in poor transmission.

Figure 7(a) shows the electric field distribution in the *xoz*-plane at 500 MHz, 700 MHz, 1.25 GHz and 1.5 GHz. It is found that in the case of 500 MHz, the electric field distribution area inside the human body is large, and the electric field intensity through the human body is strong.

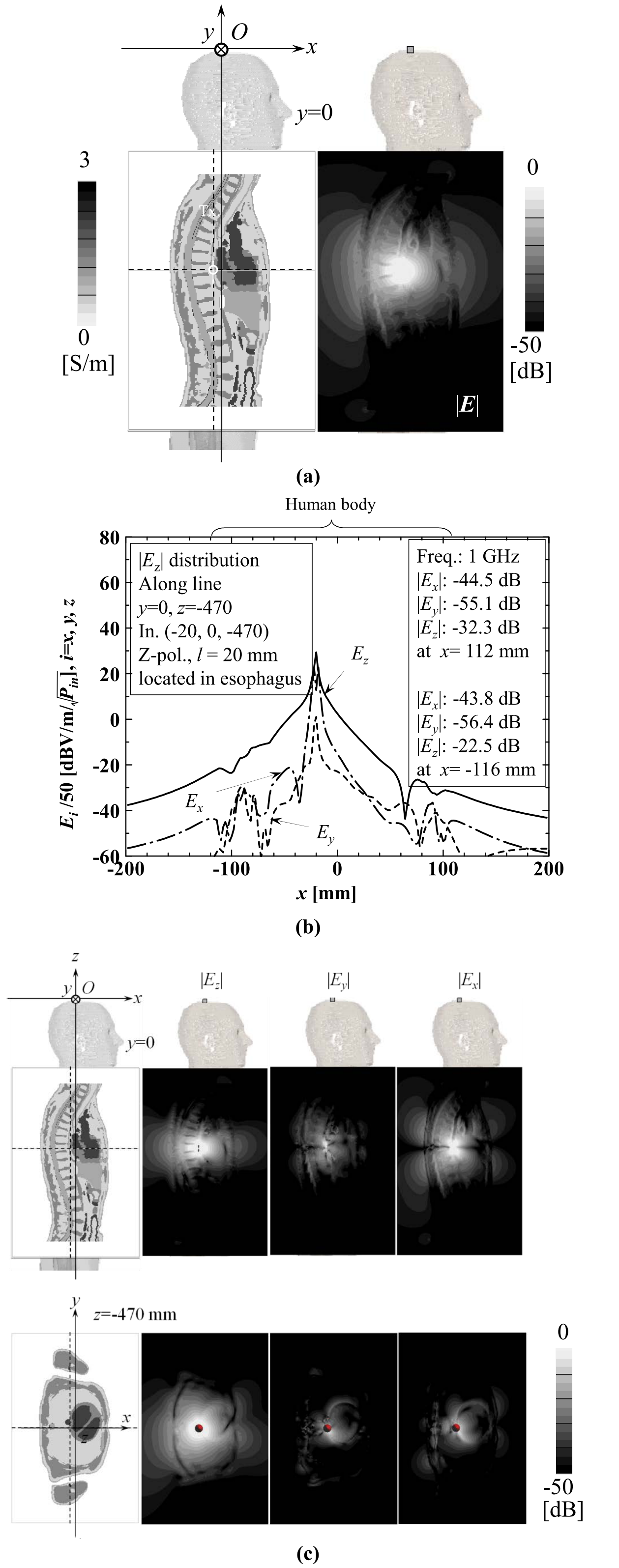

FIGURE 5. Human body conductivity distribution and electric field distribution at 500 MHz.(a) Human body conductivity distribution. (b) Electric field 1D line distribution at 500 MHz. (c) Electric field 2D plane distribution at 500 MHz.

With an increase in frequency, the electric field distribution area inside the human body becomes small, and the electric field intensity through the human body becomes weak. From Figure 6(a), it is also found that when the lungs are filled with air, the conductivity is small, and it is easy to transmit electromagnetic waves. Figure 7(b) shows the current distribution of the receiving dipole antenna. The input power is normalized to 1 W, and the impedance mismatch is not considered. It is found that the maximum value of the receiving current reaches 375 A/m^2 at 500 MHz, 250 A/m^2 at 700 MHz, 100 A/m^2 at 1.25 GHz, and 48 A/m^2 at 1.5 GHz. The results of the receiving current density in Figure 7(b) are consistent with the electric field distribution in Figure 7(a), and are consistent with the transmission factor in Figure 6.

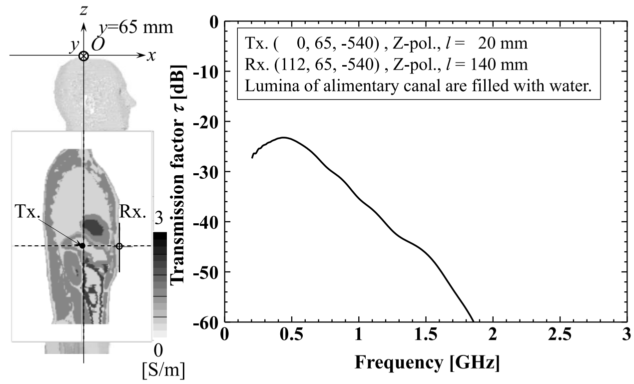

FIGURE 6. Transmission factor of capsule dipole antenna placed in the stomach (filled with water), $z = -540$ mm.

It can be concluded that when the stomach is filled with water or food with similar conductivity, the size of the implantable antenna determines the frequency where the maximum value appears, and as the conductivity of human tissues increases, the propagation of electromagnetic wave becomes weak, the intensity of the electric field distribution decreases, the receiving current density decreases, the transmission factor decreases gradually and monotonously, and the transmission effect becomes worsens.

Under the conditions that the lumina of the alimentary canal are filled with air and the capsule is placed in the stomach, the transmission factor depends on the frequency, as shown in Figure 8. It is found that the maximum value of the transmission factor is approximately -28 dB at approximately 300 MHz. Compared with Figure 8, it is noteworthy that the transmission factor has two minimum values at approximately 700 MHz and 1.5 GHz: less than -60 dB at 700 MHz and less than -50 dB at 1.5 GHz. The overall variation trend of the transmission factor with the frequency is that the transmission factor decreases as the frequency increases, but not gradually; two minimum values appear. This is because when the stomach is filled with air, the high conductivity of the stomach wall contains air lumen with

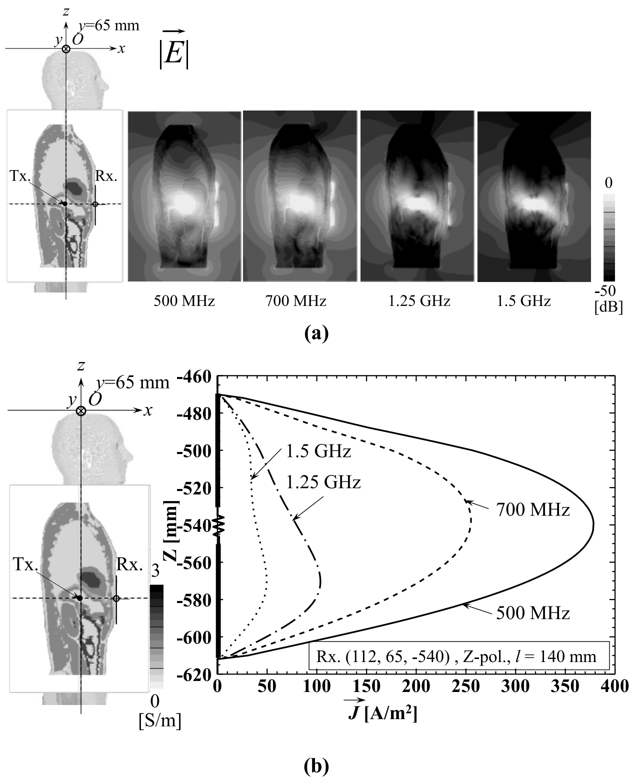

FIGURE 7. Capsule dipole antenna is placed in the stomach (filled with water, $Z_S = Z_L = 50\ \Omega$), $z = -540$ mm (a) Electric field distribution. (b) Current distribution of receiving antenna.

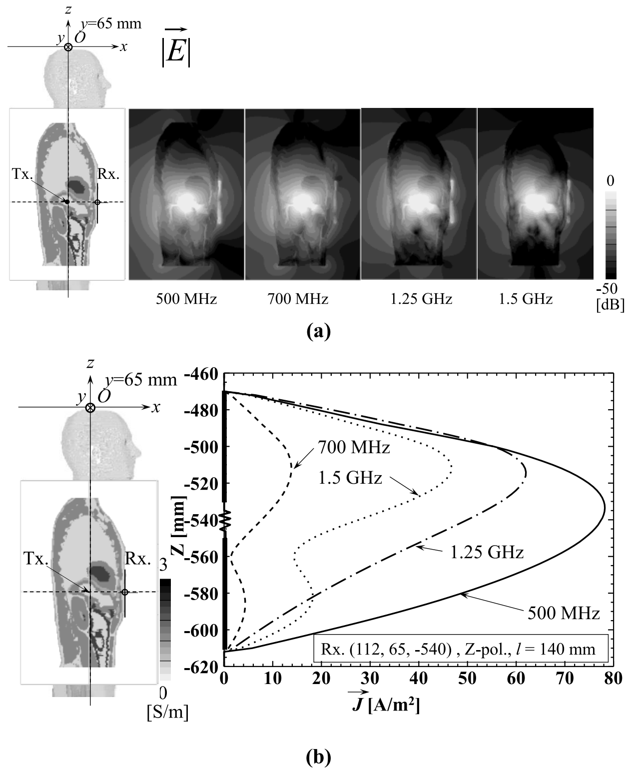

FIGURE 9. Capsule dipole antenna is placed in the stomach (filled with air, $Z_S = Z_L = 50\Omega$), $z = -540$ mm (a) Electric field distribution. (b) Current distribution of receiving antenna.

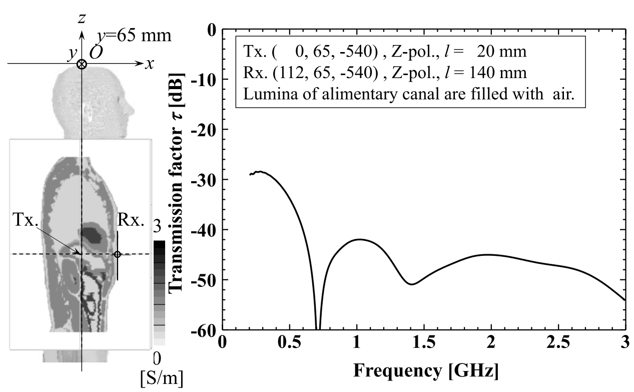

FIGURE 8. Transmission factor of capsule dipole antenna placed in the stomach (filled with air), $z = -540$ mm.

low conductivity, forming a resonant cavity. The length of the stomach is approximately 11 cm, and the λ/4 resonant frequency appears at approximately 700 MHz and the λ/2 resonant frequency appears at approximately 1.5 GHz, which explains the poor electromagnetic wave transmission.

Figure 9(a) shows the electric field distribution in the *xoz*-plane at 500 MHz, 700 MHz, 1.25 GHz and 1.5 GHz. It is found that in the cases of 500 MHz and 1.25 GHz, the electric field distribution area inside human body is large, and the electric field intensity through the human body is strong. In contrast, in the cases of 700 MHz and 1.5 GHz, because of the resonance phenomenon, the electric field distribution area inside human body is small, and the electric field intensity through the human body is weak.

Figure 9(b) shows the current distribution of the receiving dipole antenna. The input power is normalized to 1 W and mismatch is not considered. It is found that the overall receiving current density amplitude decreases compared with Figure 7(b). The maximum value of the receiving current reaches 78 A/m^2 at 500 MHz, 13 A/m^2 at 700 MHz, 60 A/m^2 at 1.25 GHz, and 46 A/m^2 at 1.5 GHz. The results of the receiving current density in Figure 9(b) are consistent with the electric field distribution in Figure 9(a), and are consistent with the transmission factor in Figure 8. The current distribution of receiving antenna under the condition that the alimentary canal filled with water is higher than that filled with air.

It can be concluded that when the stomach is filled with air, in other words, an empty stomach, the antenna size determines the frequency where the maximum value appears, and as the conductivity of human tissues increases, the propagation of the electromagnetic wave becomes weak, the intensity of the electric field distribution decreases, the receiving current density decreases, the transmission factor decreases rapidly and non-monotonously, and the transmission effect becomes worse. At special frequencies, due to the resonance, the propagation of electromagnetic waves become weak, the electric field distribution intensity decreases, the receiving current density decreases, and the transmission effect becomes worse.

To summarize, if we need to detect a gastric condition, swallowing a large amount of pure water with the electric capsule will improve the transmission effect of electromagnetic waves and will positively affect the diagnosis.

V. TRANSMISSION CHARACTERISTICS DEPEND ON DISTANCE

In Figure 10, the relationship between the received power and distance are clarified. Figure 10(a) shows a dipole-to- dipole system, an implantable dipole with total length of 20 mm and an outside dipole with total length of 140 mm. The implantable capsule dipole is placed in the stomach, where it is found that the received power decreases cubically with distance (R to the power three). In the near field region, the electric field intensity also decreases cubically with the distance. Figure 10(b) shows a loop-to-loop system, an implantable loop with total length of 40 mm and an outside loop with total length of 280 mm. When the implantable capsule loop is placed in the stomach, it is found that the received power decreases quadratically with distance (R to the power two). In the near field region, the magnetic field intensity also decreases quadratically with distance. In the far field region, the phase of the electric field and the magnetic field is the same and orthogonal. The far field electromagnetic field radiates energy outward through electromagnetic waves.

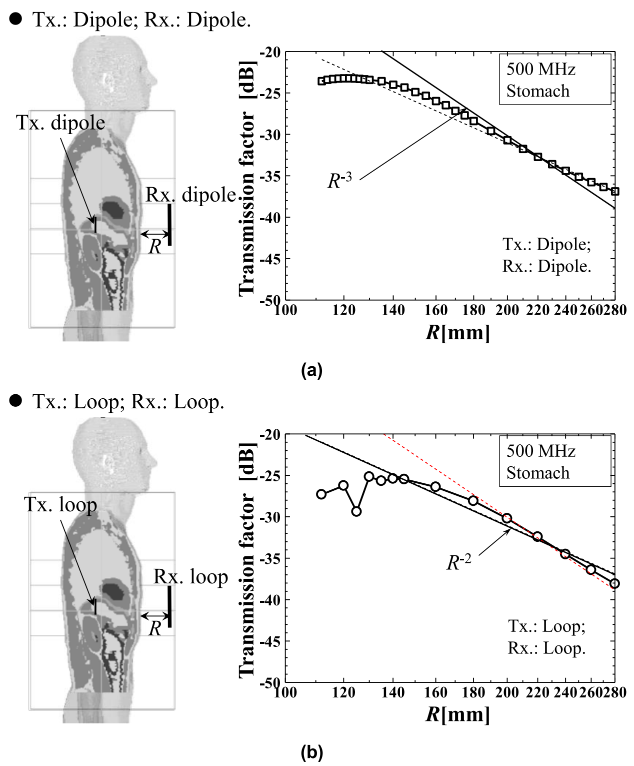

FIGURE 10. Relationship between the transmission factor and the distance. (a) Dipole-to-dipole system. (b) Loop-to-loop system.

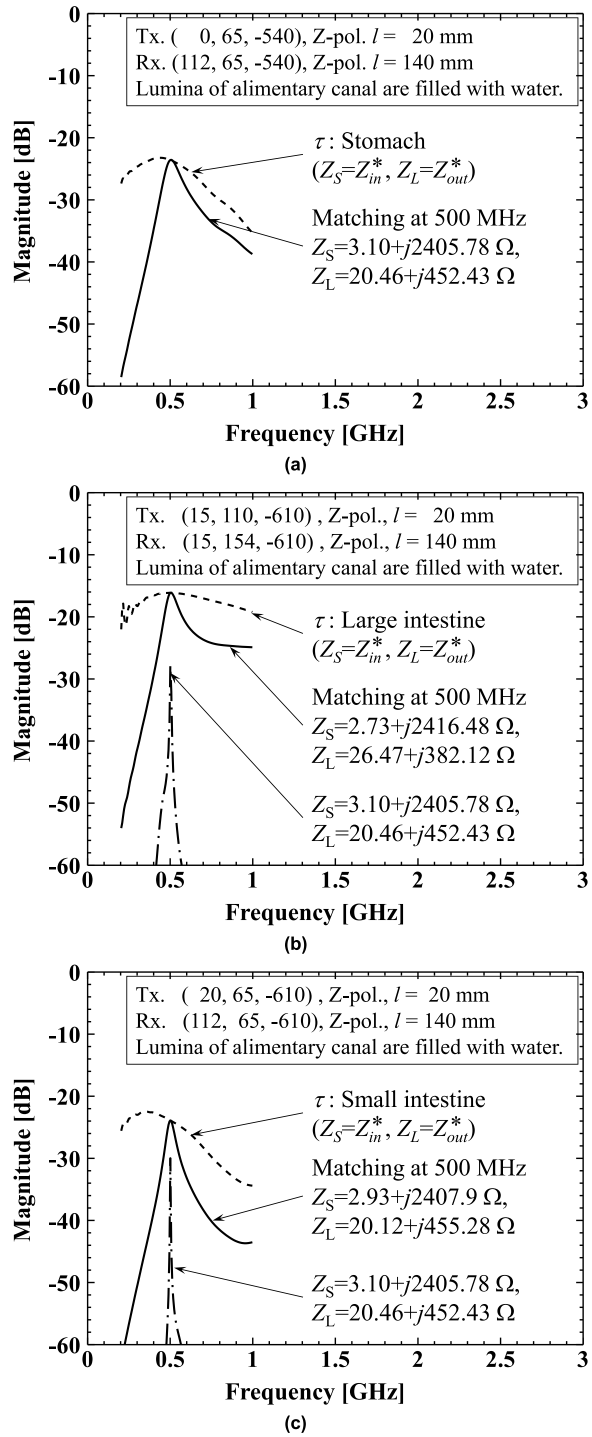

FIGURE 11. Impedance matching conditions in different organs. (a) Stomach. (b) Large intestine. (c) Small intestine.

This observation shows that the transmission effect of an electric antenna, such as a dipole, decreases slightly with an increase in distance, and the transmission effect of a magnetic antenna, such as a loop antenna, decreases greatly with an increase in distance. At approximately 500 MHz, which is the frequency is most commonly used for implantable electric capsules, the transmission effect of a dipole antenna is preferred under the condition that there is a distance between the external detection equipment and the human body.

VI. TRANSMISSION CHARACTERISTICS DEPEND ON ORGANS AND IMPEDANCE MATCHING

In this section, impedance matching by using the transmission factor τ is presented. Figure 11(a) shows the transmission factor in the stomach from 200 MHz to 1 GHz. By using an input internal and a load impedance of $Z_S = 3.10 + j2405.78\ \Omega$ and $Z_L = 20.46 + j452.43\ \Omega$, a high value of -23.58 dB can be obtained at 500 MHz. Figure 11(b) shows the transmission factor in the large intestine, by using an input internal and a load impedance of $Z_S = 2.73 + j2416.48\ \Omega$ and $Z_L = 26.47 + j382.12\ \Omega$, a high value of -16.11 dB can be obtained at 500 MHz. Figure 11(c) shows the transmission factor in the small intestine, by using an input internal and a load impedance of $Z_S = 2.93 + j2407.9\ \Omega$ and $Z_L = 20.12 + j455.28\ \Omega$, a high value of -23.89 dB can be obtained at 500 MHz. If Z_S and Z_L are not changed, for example, using constant value of $Z_S = 3.10 + j2405.78\ \Omega$ and $Z_L = 20.46 + j452.43\ \Omega$, values of -27.88 dB and -29.98 dB are obtained in the cases of the large intestine and the small intestine, respectively. Though the value decreases, the maximum frequency has not changed. When a dipole antenna placed inside the capsule passes through the alimentary canal, the matched frequency is almost unchanged.

The results show that if we need to detect an organ in the alimentary canal, we can obtain the optimum received power through impedance matching. However, if we need to detect the whole alimentary canal, the impedance matching condition for a single organ is suitable for other organs, as the matched frequency will be unchanged. As the receiving power decreases and the bandwidth narrows, it is necessary to consider other effective methods to improve the receiving power.

VII. CONCLUSION

In this research, transmission characteristics of the electromagnetic wave from an implantable antenna placed in the human alimentary canal to the outside were studied. The electromagnetic field distribution and the transmission factor of the implantable antenna placed in the in-homogeneous phantom were investigated by the FDTD analysis.

The alimentary canal includes the esophagus, stomach, small intestine, large intestine and so on, which is considered as a system. The dispersive relative permittivity of 76 human body organs is determined from 200 MHz to 3 GHz by using generic dispersive fitting. Generally, the conductivity of the heart, small intestine and large intestine is relatively large while the conductivity of the lung is relatively small. The results show that the transmission characteristics are affected by the presence of organs with high conductivity, such as the heart.

The electronic field distribution and the transmission factor are investigated under the conditions when the alimentary canal is filled with different materials. It is found that a higher value of received current distribution will be obtained when the stomach is filled with pure water than filled with air. In short, if we need to detect a gastric condition, swallowing a large amount of pure water with the electric capsule will improve the transmission effect of electromagnetic waves and will positively affect the diagnosis.

The transmission characteristics depend on the distance is clarified. In the case of a dipole-to-dipole system, it is found that the received power decreases cubically with distance in the near field region. In the case of a loop-to-loop system, it is found that the received power decreases quadratically with distance in the near field region. In short, the transmission effect of an electric antenna, such as a dipole, decreases slightly with an increase in distance, and the transmission effect of a magnetic antenna, such as a loop antenna, decreases greatly with an increase in distance. At approximately 500 MHz, which is the frequency is most commonly used for implantable electric capsules, the transmission effect of a dipole antenna is preferred under the condition that there is a distance between the external detection equipment and the human body.

Impedance matching can be obtained by using appropriate matching circuits. In different organs the optimal Z_S and Z_L are differ. When a dipole capsule antenna placed inside the capsule passes through the alimentary canal, the matched value of the transmission factor is changed while the matched frequency is almost unchanged. In short, if we need to detect an organ in the alimentary canal, we can obtain the optimum received power by making impedance matching. If we need to detect the whole alimentary canal, the impedance matching condition for a single organ is suitable for other organs, as the matched frequency will be unchanged. As the receiving power decreases and the bandwidth narrows, it is necessary to consider other effective methods to improve the receiving power.

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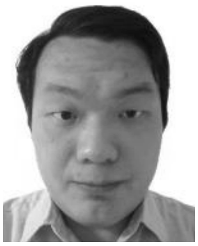
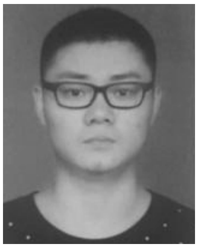


YANG LI received the B.E. and M.E. degrees from the College of Information Technology and Science, Nankai University, Tianjin, in 2008 and 2012, respectively, and the Ph.D. degree from the Department of Engineering, Tohoku University, Sendai, in 2017. He is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. His research interests include antenna design, electromagnetic wave propagation, and sensor networks.

WENQING DUAN is currently pursuing the bachelor's degree with the College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin, China.

She is participating in the Excellent Students' Training Project and the Future Engineer's Training Project. Her current research interests include wireless communication, electromagnetic wave propagation, and sensor networks.



LICHENG YANG is currently pursuing the bachelor's degree with the College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin, China.

He is participating in the Excellent Students' Training Project and the Future Engineer's Training Project. His current research interests include wireless communication, electromagnetic wave propagation, and sensor networks.

XIAONAN ZHAO received the Ph.D. degree from Tianjin University, Tianjin, in 2015. He is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. His research interests include wireless communication channel measurement and modeling.