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The Effect of Location of an Ingested Source in a Human Body Model on Electromagnetic Propagation

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Abstract

Electromagnetic fields, radiated from an intestine-ingested source and propagated through an inhomogeneous human body model, are computed with the finite-difference time-domain (FDTD) method. The calculated results obtained at some receiving points vertically placed according to the abdomen of the human body model show unusual dip patterns in the frequency domain. The frequency of this unusual dip varies according to the location of the receiving points. Thus, the relationship between the frequency of the unusual dip and the incident angle of the line-of-sight is analyzed. The effect of the location of an ingested source on the above relationship is also investigated. The slope of the approximately linear relationship is affected by the location of the ingested source.

Key words: Capsule Endoscope, Electromagnetic Propagation, FDTD, Human Body.

Ⅰ. Introduction

Capsule endoscopes [1] have attracted the interest of many research groups because they allow diagnosis of small bowel pathology such as Crohn's disease, which is impossible to detect with a traditional endoscope with a camera-attached cable [2]. Real time diagnosis is also possible, with minimum restriction on daily activities. Capsule endoscopy is also a painless and more comfortable alternative to traditional endoscopy.

The propagation characteristics of electromagnetic fields radiated from an ingested or implanted wireless biomedical device through an inhomogeneous and complex human body have been extensively investigated. Attenuation [3, 4], radiation efficiency [5], and radiation intensity [6] of electromagnetic fields have been numerically and experimentally studied. The path loss model [7] of the biotelemetry radio link has been analyzed and the dominant propagation path and the interference of electromagnetic fields propagated through a human body model have been numerically investigated [8].

The tracking of the position of a capsule endoscope in the gastro-intestinal (GI) tract of a human body is important for finding the exact location of the pathology. The use of a magnetic marker [9] was previously investigated as one possible solution, but this method required additional sensors and a magnet. Another possible solution proposed the use of amplitudes of received electric fields measured by a set of receiving antennas [2]. However, these amplitudes can vary according to the locations of the transmitting and receiving antennas due to the inhomogeneity of the human body model. Consequently, the accuracy of the determined location of the capsule endoscope could be degraded. Therefore, a supplementary method is needed to increase this accuracy.

The previously reported unusual dip patterns of received electric fields [8] can be considered as a complementary method since the frequency of each unusual dip varies depending on the location of the receiving point. This possibility is explored in the present paper by evaluating the relationship between the frequency of the unusual dip and the location of the receiving point. The effects of the location of an ingested source in the intestine of a human body model on this relationship are also analyzed.

The construction of a numerical simulator is described in Section Ⅱ. Numerically computed results obtained with the constructed simulator are presented in Section Ⅲ. The relationship between the frequency of an unusual dip and the incident angle corresponding to its receiving point is then studied. Finally, conclusions are presented in Section Ⅳ.

Ⅱ. Construction of a Numerical Simulator

The electromagnetic propagations from an intestine-ingested source in a human body model as well as corresponding phenomena are analyzed using a numerical simulator developed in our laboratory. The simulator is

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based on the finite-difference time-domain (FDTD) method [10], a human body model [8], and the dielectric properties of various organs [8] comprising the model. The human body model used here is supplied by REMCOM Inc. and is based on the transverse color images from the Visible Human Project. The frequency dependent dielectric properties of the 32 internal organs are expressed as the 1-pole Debye's formula. The vertically-polarized current density with the maximum operation frequency of 800 MHz is then excited at S in the small intestine of the human body model, as shown in Fig. 1, in place of a capsule endoscope. The waveform of the ingested current density appears as a differential Gaussian pulse.

The computation of electromagnetic fields with the progression of time uses the FDTD method. A uniform spatial resolution ($\triangle=\triangle x=\triangle y=\triangle z$) of 4 mm is taken after considering the dielectric properties of various organs and the maximum frequency of the excited current density. An air layer with $20\triangle$ is then placed between the human body model and the computational boundary, the perfect matched layer (PML) [11]. Finally, electromagnetic fields are updated with a time-step ($\triangle t$) of 0.6982 ns. This time-step is determined by considering the stability condition of the FDTD method.

The constructed numerical simulator is executed to calculate the radiated electromagnetic fields from the ingested source through the human body model. The z-components of the radiated electric fields are then saved

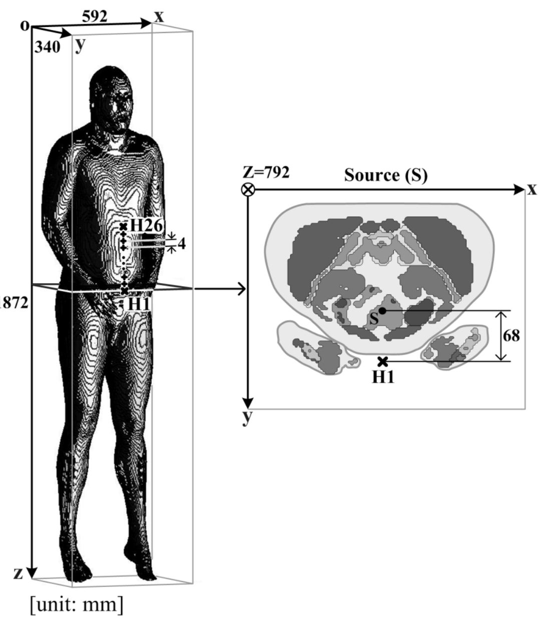

Fig. 1. Human body model with an intestine-ingested source at S and the 26 receiving points, H1-H26, on the surface of the human body model.

at 26 receiving points (H1-H26) with a dense and uniform distance step of 4 mm for accurate analysis. These 26 receiving points are vertically placed on the surface of the human body model, as shown in Fig. 1.

Ⅲ. Analysis of the Computed Results

The computed z-components of the electric fields at the 26 receiving points are transferred to the frequency domain for analysis. Unusual dip patterns are observed at some of the receiving points placed far away from the source. The normalized amplitude of the received electric field at receiving point H26 is illustrated in Fig. 2 for the frequency range of 100 MHz to 700 MHz and an unusual dip pattern is observed. In Fig. 2, the amplitude is normalized using a previously described process [8] and the frequency of the unusual dip is 230 MHz.

The unusual dip patterns are generated due to the similar amplitudes but out-of-phase characteristics of the two different kinds of waves. One is a direct wave, which propagates through a straight line connecting the source and each receiving point. The other is a surface wave, which propagates along the boundary of the human body model due to the great difference between the dielectric properties of the human body model and air. The surface wave is launched when the incident angle (θ_{inc}) of the propagated electric field shown in Fig. 3 becomes larger than the critical angle (θ_c) [8]. This means that the generation of the unusual dip is influenced by the incident angle corresponding to each receiving point. The incident angles of the 26 receiving points are expressed in Table 1 and can be seen to increase gradually for receiving points that are more distant from the source.

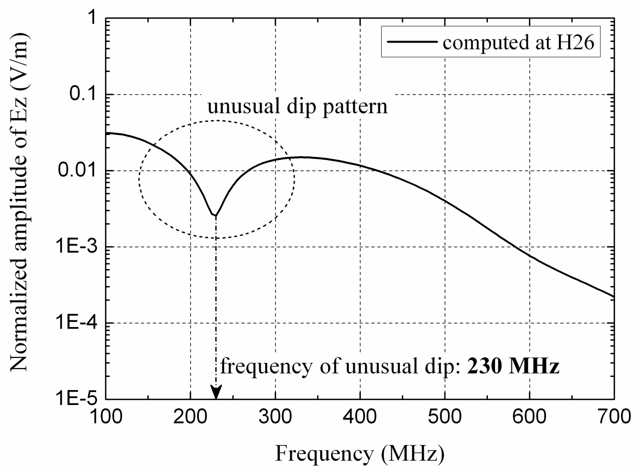

Fig. 2. Observed unusual dip pattern of the computed electric field at the receiving point, H26.

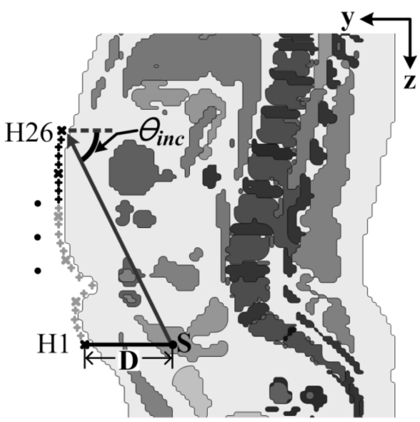

Fig. 3. Vertical cross-section of the human body model illustrating the incident angle (θ_{inc}) between an ingested source within the intestine and one of the receiving points, H26.

Table 1. Incident angle (θ_{inc}) corresponding to each receiving point in the case shown in Fig. 1.

Receiving point	Incident angle	Receiving point	Incident angle
H1	0°	H14	48.503°
H2	6.339°	H15	50.600°
H3	11.887°	H16	52.523°
H4	16.699°	H17	54.293°
H5	22.836°	H18	55.923°
H6	27.758°	H19	57.426°
H7	36.870°	H20	58.815°
H8	41.186°	H21	60.100°
H9	40.101°	H22	61.294°
H10	41.987°	H23	62.402°
H11	43.603°	H24	63.435°
H12	45.000°	H25	65.376°
H13	46.220°	H26	66.250°

The relationship between the incident angle and the frequency of the unusual dip presented in Fig. 4 is approximately linear. The frequency of the unusual dip decreases gradually as the incident angle increases. This tendency occurs because the extended line-of-sight distance according to the increased incident angle is inversely proportional to the frequency of the unusual dip. A linear fit of the relationship is then computed and added to Fig. 4. The slope of the linear fit is −0.0618.

Additional analysis on the effects of the location of the ingested source is provided by moving the location of the ingested source S in Fig. 1 to forward (S_f) and backward (S_b) directions with distance steps of 8 mm. Thus, the distance (D) between the source location S_f

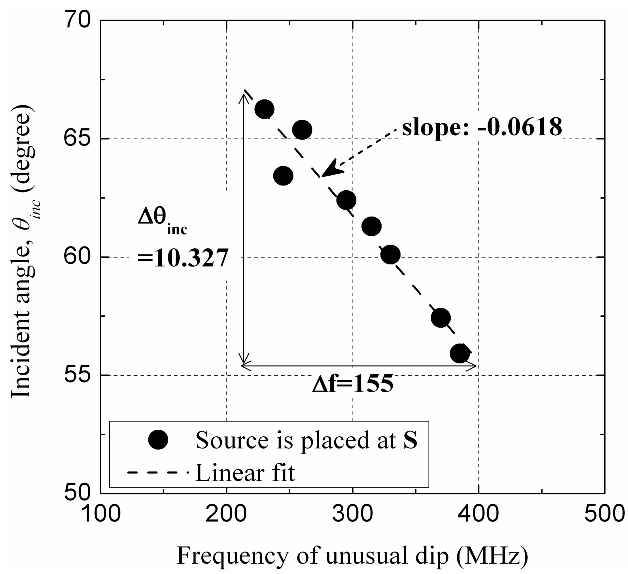

Fig. 4. The relationship between the frequency of the unusual dip and the incident angle corresponding to each receiving point as well as the computed linear fit when the source is placed at S.

and receiving point H1 is 60 mm and the distance (D) between the source location S_b and receiving point H1 is 76 mm. However, the position of each of the 26 receiving points is not changed. The corresponding FDTD simulations are also performed here.

An approximately linear relationship is obtained between the frequency of the unusual dip and the incident angle corresponding to each receiving point, even though the source location is changed. The relationships for the source positions S_f and S_b are illustrated in Figs. 5 and 6, respectively. The linear fit of each relationship is computed and added to Figs. 5 and 6. However, the slope of each linear fit is different. In Fig. 5, the slope of the linear fit is −0.0338 while it is −0.0790 in Fig. 6. This means that the frequency of an unusual dip depends on the location of the ingested source as well as on the receiving point. The dip pattern was generated under the condition where the surface wave had a similar amplitude, but was also out-of-phase with the direct wave [8].

When the source moves forward to the anterior of the human body model, the attenuation of the direct wave is reduced. Thus, the unusual dip is observed at a relatively far receiving point, which has a large incident angle. Consequently, the degree of variation in incident angle (θ_{inc}) decreases as the source moves in the forward direction. Therefore, the slope that is affected by the variation in the incident angle (θ_{inc}) decreases gradually as the ingested source moves in the forward direction, as shown in Figs. 4, 5, and 6. This leads to the conclusion that these relationships can be used as a sup-

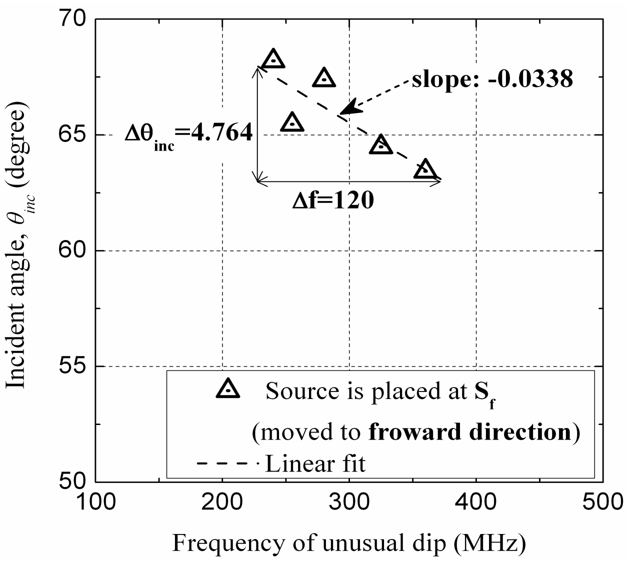

Fig. 5. The relationship between the frequency of the unusual dip and the incident angle corresponding to each receiving point as well as the computed linear fit when the source is placed at S_f.

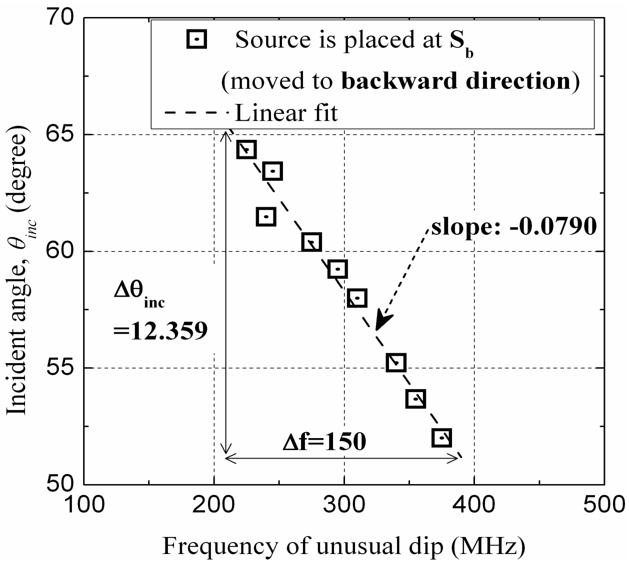

Fig. 6. The relationship between the frequency of the unusual dip and the incident angle corresponding to each receiving point as well as the computed linear fit when the source is placed at S_b.

plementary method to find the location of an ingested source. However, more simulations will be needed to generate accurate relational expressions.

Ⅳ. Conclusions

Electromagnetic fields radiated from an intestine-ingested source were computed and saved at 26 receiving points vertically placed along the abdomen of a human body model. The relationship between the frequency of an unusual dip in the received electric field and the incident angle corresponding to its receiving point was then analyzed and yielded an approximately linear association. The computed slope of each linear fit varied according to the location of the ingested source. The computed slope decreased gradually as the location of the ingested source moved to the boundary of the human body model. These approximately linear relationships are expected to be useful as a supplementary method for finding the location of an ingested source. These relationships will be further analyzed in the case of transversely and longitudinally polarized sources to obtain more accurate and generalized information.

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