Magnetic loop antenna for wireless capsule endoscopy inside the human body operating at 315 MHz: Near field behavior

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Abstract—**In ingestible systems, the antenna suffers from deterioration of performances due to surrounding dissipative tissues. A small circular magnetic loop antenna, whose diameter is equal to 1 cm and thickness is equal to 0.5 mm operating at the frequency of 315 MHz in the ISM band, is proposed to limit this degradation. The electric properties of the human body, having a high dielectric constant and low impedance, are considered to design and simulate the loop antenna. We found that the magnetic field is less attenuated than the electric field in the human body that improves the signal level received by near field magnetic coupling.**

Keywords-Homogeneous human body, magnetic loop antenna, near field magnetic coupling, ingestible capsule.

I. INTRODUCTION

Wireless transmission systems are more and more employed in telemedicine inside and outside the human body for medical diagnostics and therapeutic follow-up for diverse applications such as retinal prostheses, hyperthermia, pacemakers, implantable defibrillators, capsule endoscope and wearable medical devices including heart rate, blood pressure, blood oxygen saturation and respiration monitors [1, 2]. The wireless capsule swallowed by the patient, make it possible to control the completeness of the gastro-intestinal tract through sent images at real time instead of classical endoscopy which is uncomfortable for the patient and unable to examine the major part of the small intestine [3]. This ingestible wireless system contains several modules: light emitting diodes (LEDs), CMOSs, transmitter, antenna, batteries, etc [4], associated in an image-emitting capsule, while it is moving in the gastrointestinal (GI) tract, to a receiving antenna in the exterior of the human body. The ISM (Industrial, Scientific and Medical) frequency bands allowed to these capsules are 434 MHz, 868 MHz and 2.4 GHz in Europe and 315 MHz, 915 MHz and 2.4 GHz in U.S. [3]. The endoscopic capsule operates inside the human body, which is a dissipative multi-layer medium having electric properties different to these of free space: it has a conductivity, which is different to zero and a high dielectric constant. The antenna employed in these capsules must be miniaturized and the electric properties of the human body, which are going to modify the antenna performances (radiation pattern, resonant frequency, radiation efficiency…), must be considered to design the antenna [5]. The electromagnetic wave absorption increases at high frequencies, increasing the antenna power consumption. The magnetic field is less absorbed by the human body: the use of the near field magnetic coupling permits to decrease the transmission losses and increases the battery life of the capsule [6].

It is interesting to focus on the wireless links between capsule antennas and exterior receivers. In a first study [7], the radiated energy by a capsule antenna and the E field attenuation in the human body are investigated versus the frequency (430 MHz, 800 MHz and 1200 MHz), the antenna orientation and the capsule position in a small intestine. It is known that the radiated energy is more absorbed by the human body when the frequency is high. However, in this study, it is observed that the radiated energy depends also on the orientation of the capsule versus the polarized electric field in the far field and on the position of the capsule in the GI tract, because of the antenna impedance mismatching. The low-frequency antennas, like the magnetic antenna (the coiled antenna or helix antenna, etc), suffer from slow rate data, short range communication inductive link and magnetic power decreases with the sixth power of the distance [8]. However, the magnetic power is independent of the properties of the channel [9], contrary to the RF power whose attenuation depends on the permittivity of the dissipatif medium. Also, the magnetic power can be optimised at the reception in function of antenna properties [8].

In this paper, the behavior of a small loop antenna operating at the 315 MHz ISM band is investigated in the near field. The total magnitudes of the electric and magnetic field are estimated according to the distance z (z-axis is normal to the antenna plane) as well as the impedance (E_{total} / H_{total}). The electric characteristics of the human body, which depend on the frequency, are taken into account.

II. ELECTRIC CHARACTERISTICS OF THE HUMAN BODY

The human body is a multilayer medium constituted of different organs such as muscles, bones, blood, cells, skin, stomach, etc. Every layer contains its own electric properties, which also depends on the frequency. To simplify the ingestible antennas study (inside the human body), the different layers of the human body can be associated in only one homogeneous

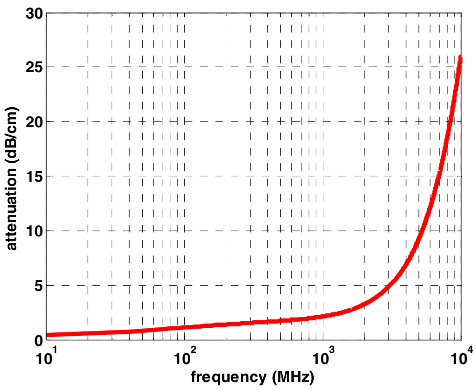

Figure 1. Attenuation of an electromagnetic wave according to the frequency in the muscle (from 10 MHz to 10 GHz)

layer, which is the muscle [5]. The complex dielectric constant of the muscle (1) depends on the frequency; it is calculated with the 4-cole-cole method [10]. The relative permittivity (real part of (1)) and the conductivity (proportional to the imaginary part of (1)) values are then deducted. The attenuation of an electromagnetic wave in the muscle is also calculated according to the frequency (Fig. 1). This curve shows that the attenuation in the muscle increases with the frequency particularly at high frequencies (beyond 1 GHz); at 315 MHz, the attenuation value is 1.56 dB/cm. At the same frequency, the relative permittivity, calculated in the muscle, is 58, the conductivity is 0.77 S/m and the impedance value, given by (2), is 44.15 Ω (32.9 dBΩ).

$$\underline{\varepsilon}_r = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0} \qquad (1)$$

$$Z = \frac{Z_0}{\sqrt{\underline{\varepsilon}_r}} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \qquad (2)$$

Where: $Z_0 = \sqrt{\mu_0/\varepsilon_0}$ and $\varepsilon = \varepsilon_0\varepsilon_r$

III. Design of the Magnetic Loop Antenna Inside the Human Body

The loop antenna, which presents higher magnetic H field amplitude in the near field, than this one of an electric dipole, is chosen in this study. The impedance, given by the ratio between the electric and magnetic field (3), will thus decrease. The ratio of (3) corresponds to the wave impedance of a transverse electromagnetic wave propagating in the z direction.

$$Z = \frac{E_x}{H_y} \qquad (3)$$

The impedance of the high permittivity human body, which is inversely proportional to the square root of the permittivity of the medium (2), is weak also with regard to this one of the air (120π Ω for a transverse electromagnetic wave). The magnetic energy coupling inside the human body will be favored. In [11], it is revealed that the classic limit of the near field ($r<\lambda/2\pi$) is not accurate and that this limit can be extended until 1.6λ for the λ/10 dipoles. In the human body, the physical lengths of the antenna increase because the wavelength inside the human body is inversely proportional to the square root of the relative permittivity of the medium: this explains the miniaturization of the ingestible antennas operating in the human body. This is a very important parameter because the dimensions of the antenna are limited by these of the capsule, whose diameter is equal to 10.1mm [5]. Thus, the total diameter of the antenna should not exceed this value.

The circular magnetic loop antenna is designed and simulated using HFSS (High Frequency Structural Simulator) which is based on the Finite Element Method (FEM). The dielectric substrate Roger RT/duroid 5880 having a relative permittivity ε_r of 2.2, a dielectric loss of 0.0009, a thickness of 0.508 mm and a diameter of 1 cm is used to design the antenna (Fig. 2. d). The metallic thickness is 17.5 µm. The magnetic antenna consists of two concentric loops with a same width (w_1) equal to 0.25 mm, spacing by a distance (a) of 0.25 mm, localised in the center of the (xoy) plane in the upper side of the substrate (Fig. 2. c). The greater loop has a radius (r_2) of 4.47 mm and the second loop's radius (r_1) is 3.97 mm. A capacitance of 7.9 pF is used for such loop to adapt the antenna at the operating frequency. This antenna is fed by electromagnetic coupling to amplify the input impedance, which is very low due to the reduced dimensions of the magnetic loop. The antenna's input impedance depends on the dimensions of the feed loop and the spacing between the radiating element and the feed element [12]. The feed loop, whose radii (r_3) is 1.9 mm and width (w_2) is 0.2 mm, is localised at the same side of the antenna. The distance between the two elements of the antenna is adjusted to adapt the antenna's input impedance to a 50 Ω cable at 315 MHz. The antenna is inserted inside a cylinder having the sizes of a capsule (vitamin pill) filled with air (Fig. 2. b), positioned in the center of a cubic box, with ε_r = 58 and σ = 0.77 S/m (Fig. 2. a), representing the muscle at 315 MHz. To investigate the variation of field magnitudes in free space and the human body, the simulation has been occurred at three different environmental conditions. The first consists to insert the loop antenna in the center of a 32 cm × 32 cm × 32 cm box, representing the homogeneous human body, surrounded by an air-box whose dimensions are 64 cm × 64 cm × 64 cm (human body / air). In the second case, the antenna is positioned in the center of a 50 cm × 50 cm × 50 cm box representing the human body. The third condition consists to simulate the capsule antenna directly in an air box whose dimensions are 64 cm × 64 cm × 64 cm. The antenna return losses, in the three cases, are plotted in Fig. 3. In the first case, the magnetic loop antenna is adapted to a 50 Ω cable close to 315 MHz; the bandwidth calculated at -10 dB is equal to 2 MHz. In the second case, the frequency shift is due to the box dimensions change (human body). When the antenna is placed in the air, the frequency is just a little shifted because the antenna is first inserted in the capsule (air) before to be in contact with the human body. Whereas, the frequency shift in the air should be more important if the antenna was positioned directly in the human body (without capsule). In free space, the antenna is not adapted to a 50 Ω cable; the investigated frequency, to measure the field magnitude variations, is the frequency, which presented the lowest S_{11}.

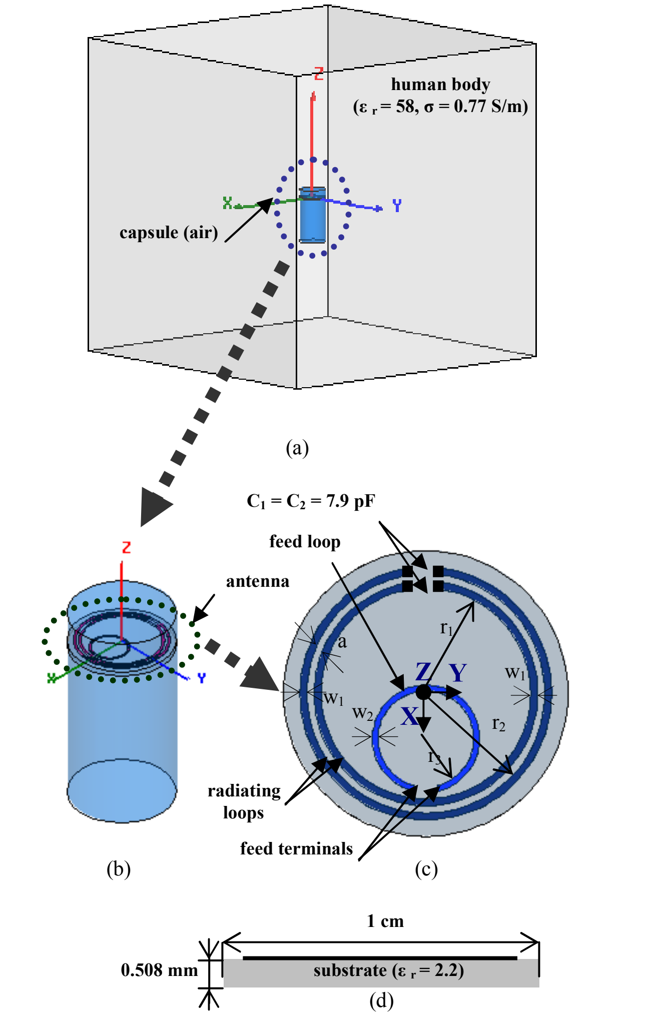

Figure 2. (a) Capsule inside a box modelling the human body/ (b) Antenna inside the capsule filled with air/ (c) Antenna geometry/ (d) Longitudinal section of the antenna (the images are not in the scale)

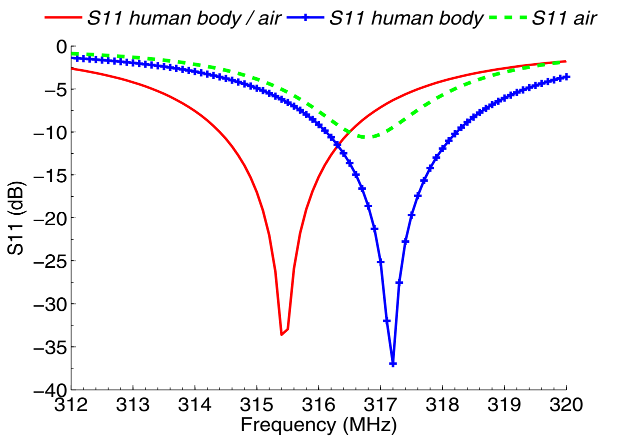

Figure 3. Simulated return losses of the magnetic loop antenna in the human body / air, the human body and free space

IV. Electric and Magnetic Field Behavior of the Loop Antenna in the Near Field Region at 315 MHz: Simulation Results

The different components of the electric and magnetic field as well as the total H field and the total E field components are plotted according to the distance in the z direction in the three cases reported in the paragraph 2. We note impedance the ratio from the total electric field component by the total magnetic field component in every medium [13], but it doesn't correspond in the near field to the wave impedance of a transverse electromagnetic wave.

A. First case : Antenna in the human body / air

We remind that the antenna is first placed in a box representing the homogeneous human body surrounded by an air box. Fig. 4 shows that the y component of the electric field is dominant, thus the E total field is close to this transverse component.

Concerning the magnetic field, the z component is dominant and the H total field is almost equal to this longitudinal component (Fig. 5).

The total E field decreases in the human body with the distance below z = 16 cm, if the distance is higher than this limit (in the air), the total E field decreases less quickly. Whereas, the magnetic field is still linearly decreasing in the air until z = 24 cm (Fig. 6). Thus the difference between the electric and magnetic field increases beyond 16 cm.

Fig. 7 confirms that the impedance in the air is higher than this one in the human body. The Z (Etotal / Htotal) value increases from 20 dBΩ in the human body to 35 dBΩ in the air. In the origin of the loop, the impedance varries from 12 dBΩ to -10 dBΩ at z = 0.5 cm, this is due to the low air volume inside the capsule in which the antenna is inserted. Then the impedance increases slowly, in the human body region, until almost 20 dBΩ at 16 cm.

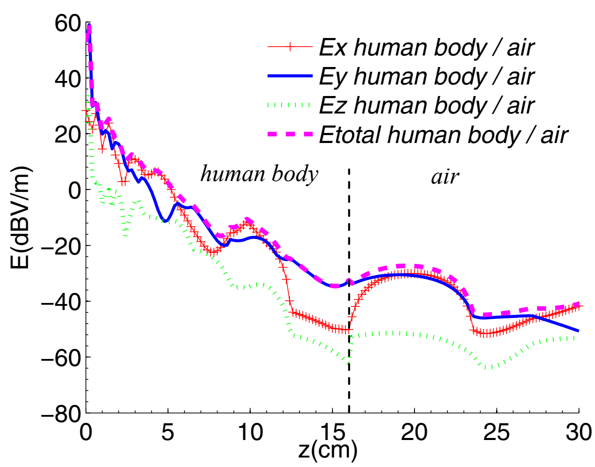

Figure 4. Electric field components and total electric field of the loop antenna versus the z distance in the human body / air

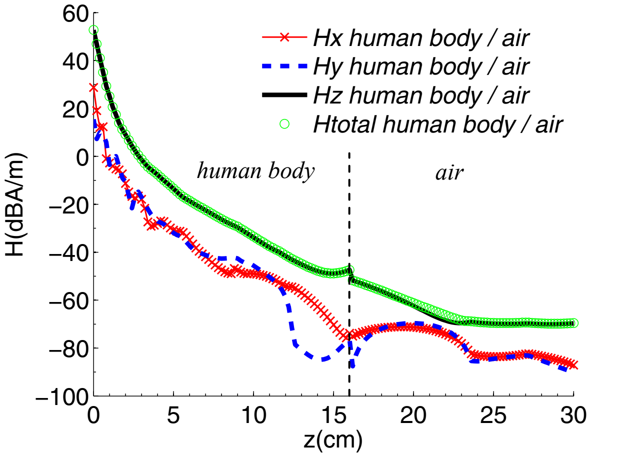

Figure 5. Magnetic field components and total magnetic field of the loop antenna versus the z distance in the human body / air

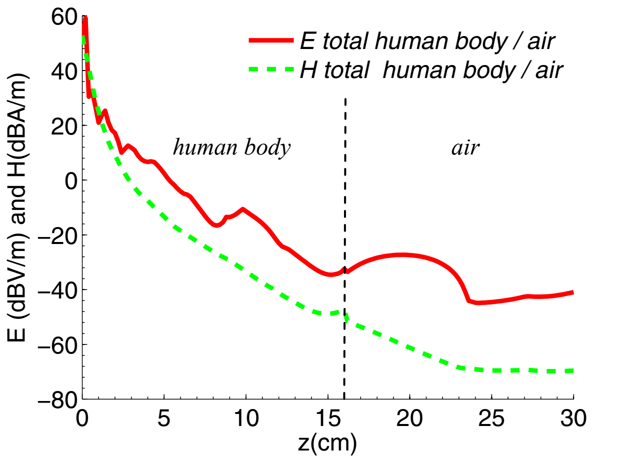

Figure 6. Total electric field and total magnetic field of the loop antenna versus the z distance in the human body / air

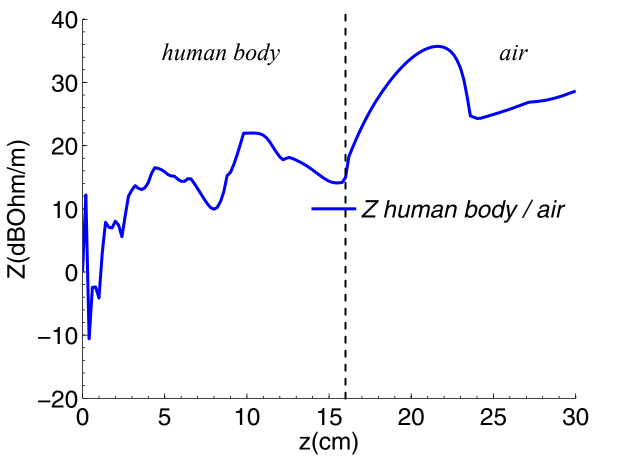

Figure 7. Z impedance (Etotal / Htotal) of the loop antenna versus the z distance in the human body / air

B. Second case: Antenna in the human body

When the antenna is placed only in a bigger box representing the homogeneous human body, we note that the electric field is more perturbed than that in the first case. The Ey component is always dominant (Fig. 8) in this case, too.

Fig. 9 shows that the H total field in the human body is also almost equal to the longitudinal component Hz.

The variations of the total electric field component and the total magnetic field component versus the distance are both linear over 7 cm and the difference between the two components is still stable in this zone until 25 cm (Fig. 10).

The approximated impedance, in this case, is also plotted in Fig. 11. The impedance increases until z = 11 cm, then, it presents weaker variations. We can conclude that, the near-field region can extend at least at this distance (11 cm).

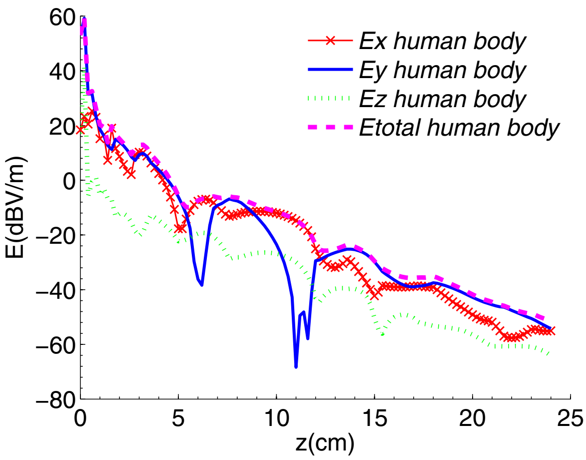

Figure 8. Electric field components and total electric field of the loop antenna versus the z distance in the human body

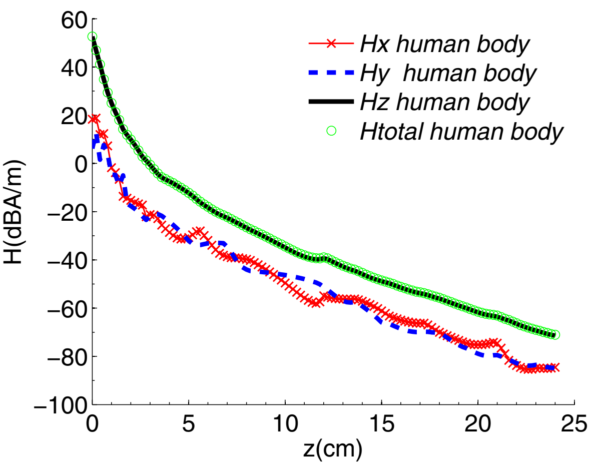

Figure 9. Magnetic field components and total magnetic field of the loop antenna versus the z distance in the human body

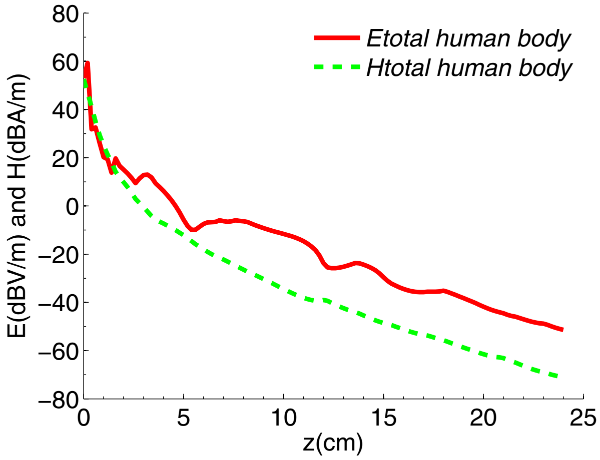

Figure 10. Total electric field and total magnetic field of the loop antenna versus the z distance in the human body

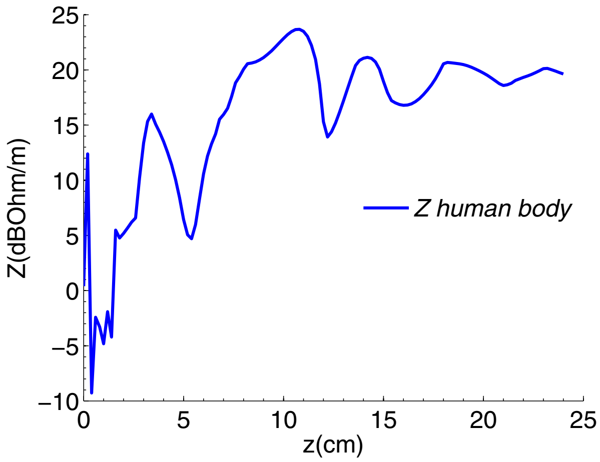

Figure 11. Z impedance (Etotal / Htotal) of the loop antenna versus the z distance in the human body

C. *Third case: Antenna in free space*

In free space, below a distance z of 8 cm, the Ey component is always dominant. Further than this distance, the Ex component becomes dominant. The E total component follows the dominant component (Fig. 12). The electric field is less perturbed in the air.

The z component of the magnetic field, which is almost equal to the H total component, is still also dominant in this case (Fig. 13).

Below 10 cm, both total electric and total magnetic field components decrease quickly but the difference between the two components increases. Over this limit, the difference between the two components becomes more stable (Fig 14) and is more important than that in the human body.

The impedance increases in the air when the distance varies between 0 and 11 cm (0.11*λ0). Consequently, this region belongs to the near-field zone (Fig. 15).

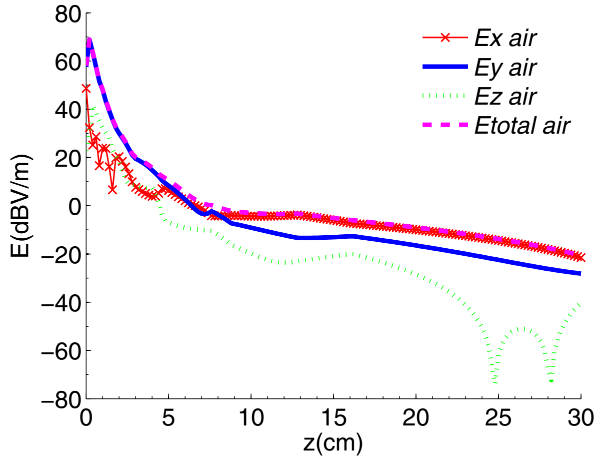

Figure 12. Electric field components and total electric field of the loop antenna versus the z distance in the air

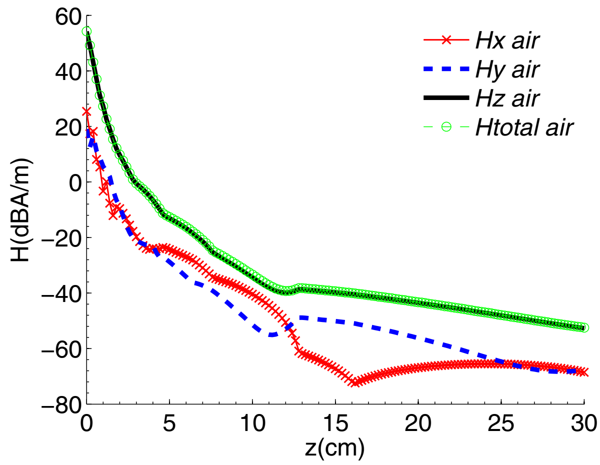

Figure 13. Magnetic field components and total magnetic field of the loop antenna versus the z distance in the air

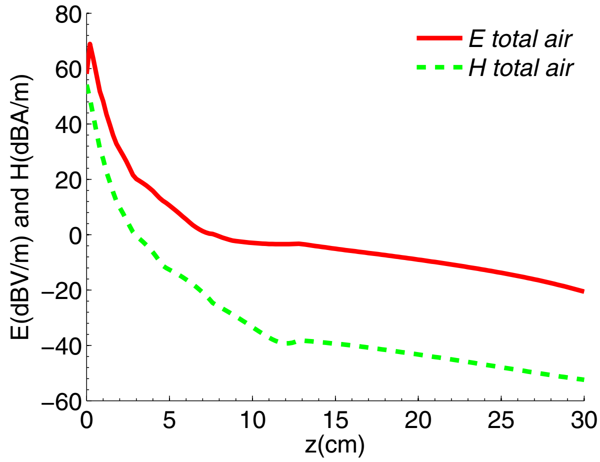

Figure 14. Total electric field and total magnetic field of the loop antenna versus the z distance in the air

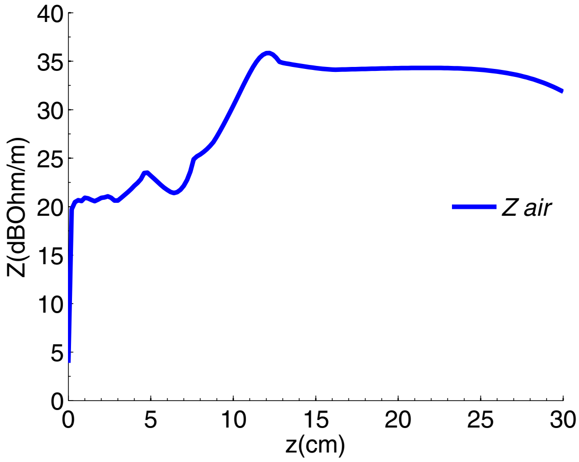

Figure 15. Z impedance (Etotal / Htotal) of the loop antenna versus the z distance in the air

D. *Comparative study between the antenna inside the human body and in free space*

To show the influence of a dissipative medium, such as the human body, on the magnetic loop antenna's field behavior, a comparative study is established.

The behavior of the total electric field according to the z distance, in the three cases of environmental simulation conditions, is given by Fig. 16. It is clear from these plots, that the electric field is very absorbed by human tissues especially above 12 cm. At a distance of 24 cm, the difference between the total electric field in free space (solid line) and that in the human body (marked line with the 'x' symbol) achieves 40 dBV/m.

However, the magnetic field is less absorbed by human tissues as shown in Fig. 17. The magnetic field is almost not absorbed by biological tissues until a distance z from the antenna equal to 12 cm. Over this limit, the total magnetic field begin to be slowly absorbed by the human tissues and the difference between the total magnetic field in free space (solid plot) and this one inside the human body (marked line with the 'x' symbol) is only equal to 23 dBA/m at a distance z equal to 24 cm.

Fig. 18 presents a comparison between the approximated impedance (Etotal / Htotal) variation versus the distance in the three cases of environmental simulation conditions. The dotted line curve shows that the impedance in the human body zone (first simulation condition, z between 0 and 16 cm) is close to the impedance of the antenna placed in the human body (second simulation condition) given by the marked line with the 'x' symbol. Beyond this distance (dotted line in the zone of air), this impedance reached quickly the impedance of the capsule loop antenna placed directly in the air (solid line in Fig. 18, third simulation condition).

We can conclude from Fig. 17 and Fig. 18 that the magnetic coupling is effective at least until a distance z of 11 cm, region in which the impedance values are not still constant.

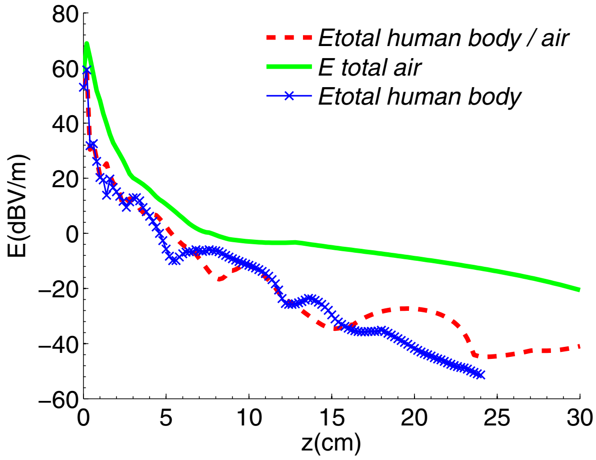

Figure 16. Total electric field of the loop antenna versus the z distance in the human body / air, the human body and the air

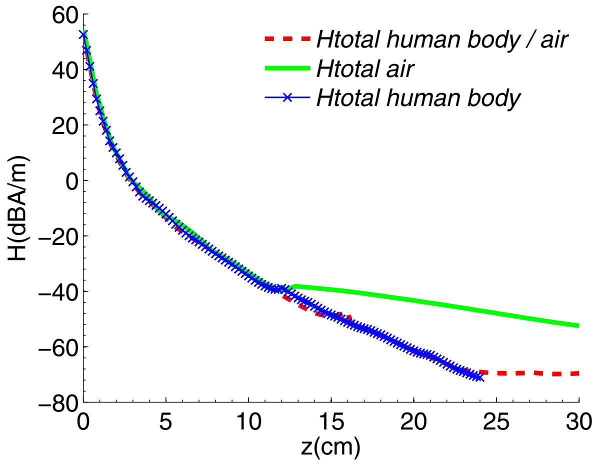

Figure 17. Total magnetic field of the loop antenna versus the z distance in the human body / air, the human body and the air

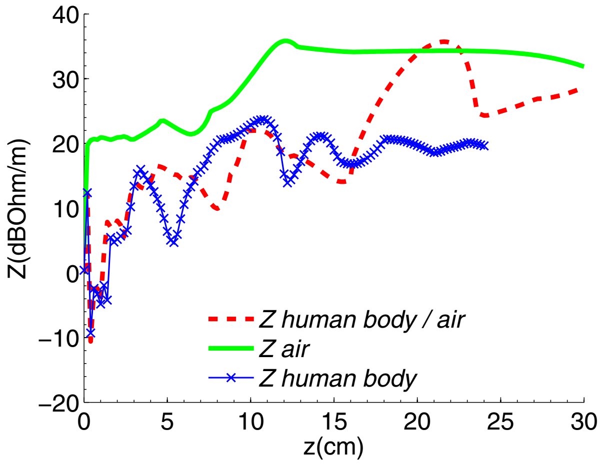

Figure 18. Impedance (Etotal / Htotal) of the loop antenna versus the z distance in the human body / air, the human body and the air

V. CONCLUSION

Through the use of numerical simulations, a low profile magnetic loop antenna is shown to be suitable for the capsule endoscopy systems. The characteristics of the human body, which are considered in simulations, are studied at first. Then, the antenna is simulated inside the human body and in free space. At last, the electric and magnetic field behavior is investigated in the near field region. It is demonstrated that the magnetic field is less absorbed by human tissues than the electric field. At a distance of 12 cm from the antenna, the magnetic field is still not absorbed by biological tissues and the attenuation of the magnetic field is still in acceptance level until important distances. The results confirm that the proposed antenna is suitable for the near field magnetic coupling in the capsule endoscopy systems. In order to characterize the propagation channel inside the human body in term of attenuation and dispersion, the design of a magnetic receiving antenna is going to be studied. To take into account, the fact that the endoscopic capsule can be rotated inside the gastrointestinal tract, a 3-D antenna should be an advantage. This antenna should present a larger bandwidth to allow the video data transmission and to take into account the frequency shift due to the various layers which compose the human body. A magnetic substrate could be used to design the antenna in order to maximize the bandwidth and minimize the sizes of the antenna. In this study, at a first time, the body is considered as a uniform model. In future works, the study of a capsule antenna, in a multilayer phantom, whose dielectric constant and conductivity of different layers, depend on the frequency, should allow observing the eventual variations due to the presence of inhomogeneous layers. The variability of the dielectric properties of the phantom, in presence of the capsule, when it is moving, can result in the antenna impedance mismatching. So the association with a retro-matched system should be a good alternative, in order to ensure adequate power transfer. The orientation and the position variations of the capsule, ingested in the human body, should be associated to this study to correctly consider the influence of all these parameters on the capsule-receiver link. An association with a captor, that measures vital signals of the patient (pH, pressure, temperature, etc) for medical monitoring, could be the ultimate aim of this study.

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