Operation of Ingestible Antennas along the Gastrointestinal Tract: Detuning and Performance

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***Abstract*—In this study, we numerically assess detuning issues for an ingestible antenna which is designed to operate in the Medical Device Radiocommunications Service (MedRadio, 401–406 MHz), as it travels along the gastrointestinal (GI) tract. For this purpose, we evaluate the antenna resonance performance within four canonical single-tissue models of the human esophagus, stomach, small and large intestine. The antenna is further placed at different locations within the aforementioned tissue models in order to assess detuning issues related to its relative positioning within each of them. Inherent detuning issues are observed and discussed in the four different simplified tissue models considering three specific locations of the antenna in each model, resulting in twelve different scenarios. The resonance, radiation and safety performance of the ingestible antenna is, finally, evaluated.**

I. Introduction

WIRELESS Capsule Endoscopy (WCE) offers a feasible non-invasive way for detecting abnormalities along the entire gastrointestinal (GI) tract. Even though wired endoscopy methods offer great potential for diagnosis, they cause pain and discomfort, while leaving a big part of the GI tract totally in dark (i.e., the small intestine) [1], [2]. Therefore, apart from expanding the diagnosis and treatment capabilities of the traditional wired methods, WCE promises significant improvements in patients' care and quality of life. A Wireless Capsule (WC) incorporates several microelectronic circuits, sensors, a CMOS camera, LEDs, an antenna for wireless communication with exterior devices, batteries and even, in some experimental cases, sophisticated systems for active locomotion inside the GI tract [2]-[4]. The ingestible antenna can be considered as one of the most critical components, and careful design is required in order to miniaturize the capsule size, while obtaining robust communication links and preserving the quality of service (QoS) needed for endoscopy.

Design of ingestible antennas is a highly challenging task, since they need to: (a) be small, (b) have enough bandwidth to support high data rates for live endoscopic diagnosis, (c) achieve high efficiency in order to maintain the communication link given the power requirements imposed by international safety guidelines (IEEE Std C95.1-1999 [5] and Std C95.1-2005 [6]), (d) drain a fairly small amount of energy so that the wireless capsule can maintain its operation during the entire GI tract (typically 8 - 9 h), and (e) operate inside a "hostile" environment, i.e., the human body. When the environment surrounding the ingestible antenna changes, the effective relative permittivity of the antenna changes as well. Therefore, the exhibited resonance, radiation and safety performance can be significantly altered [7]. As the WC travels along the GI tract, several human tissues are involved, like muscle, fat and skin. As a result, the effective relative permittivity of the antenna is unpredictable and constantly changing. Moreover, the dielectric constant and conductivity of human tissues depend on frequency [8]. Thus, the ingestible antenna is expected to face detuning effects while the WC travels along the GI tract.

In this study, we attempt to quantify detuning effects for ingestible antennas caused by the change of the surrounding tissues during its way along the GI tract. A conformal ingestible antenna is studied, which has recently been proposed for operation in the MedRadio band [9]. In order to evaluate the inherent detuning effects, four canonical single-tissue models are proposed to model the esophagus, stomach, large and small intestine. Constant tissue dielectric properties are assumed within a ±100 MHz range around the MedRadio band. Finite Element (FE) simulations are carried out using Ansoft HFSS software [10].

The paper is organized as follows. Section II describes the ingestible antenna model, tissue models and FE simulation parameters, while numerical results are presented in Section III.

II. Models and Methods

A. Antenna Design

The ingestible antenna used in this study has been recently presented by the authors [9], and is shown in Fig. 1(a). The antenna model exhibits a serpentine patch geometry with the patch being printed on a flexible substrate material (Rogers RT/duroid 5880, $\varepsilon_r = 2.2$), which allows its conformance to the shape of the capsule. Thickness of the substrate layer is limited to the minimum available by Rogers (0.127 mm), for miniaturization purposes. To preserve the biocompatibility of the ingestible capsule and protect the patch from direct contact with the surrounding human tissues, the antenna is coated by a 0.1 mm-thick polyethylene coating ($\varepsilon_r = 2.25$, $\tan\delta = 0.001$). The polyethylene superstrate, which features a

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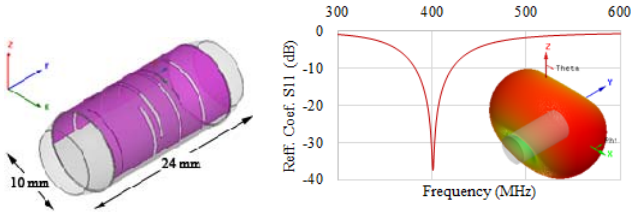
dielectric constant similar to the one used on the substrate of the antenna, enables tuning of the antenna in the MedRadio band. The radiating patch, before its conformance, is of square shape with meanders being inserted to increase the length of the current flow and decrease its size to 18 mm x 18 mm. A shorting pin is inserted to connect the patch to the ground plane, in order to further decrease the antenna size. The aforementioned antenna is considered to be wrapped around a cylindrical capsule (ingestible pill), with a length of 24 mm and a diameter of 10 mm, as shown in Fig. 1(a).



(a) (b)

Fig. 1. (a) The proposed ingestible pill. The serpentine antenna design is highlighted to show the occupied space of the radiator. (b) Reflection coefficient ($|S_{11}|$) frequency response and far-field gain radiation pattern of the proposed ingestible antenna.

When the ingestible pill of Fig. 1(a) is immersed inside a cubic tissue model which simulates muscle tissue properties at 402 MHz (εr = 57 σ = 0.8 S/m) then the reflection coefficient (|S11|) frequency response of the antenna is shown in Fig. 1(b) [9]. The antenna resonates at the MedRadio Band (-37.51 dB at 402 MHz) and exhibits a 10dB-bandwidth of 9.9%. The antenna far-field gain radiation pattern is presented in Fig. 1(b). A maximum far-field gain value of -29.64 dB is recorded. Finally, the Specific Absorption Rate (SAR) is assessed within the cubic muscle-tissue model in order to provide further insight into patient safety issues. Assuming a net input power of 1 W incident to the antenna, the maximum 1-g-averaged and 10-g-averaged SAR values are found to be equal to 417.55 and 86.65 W/kg, respectively.

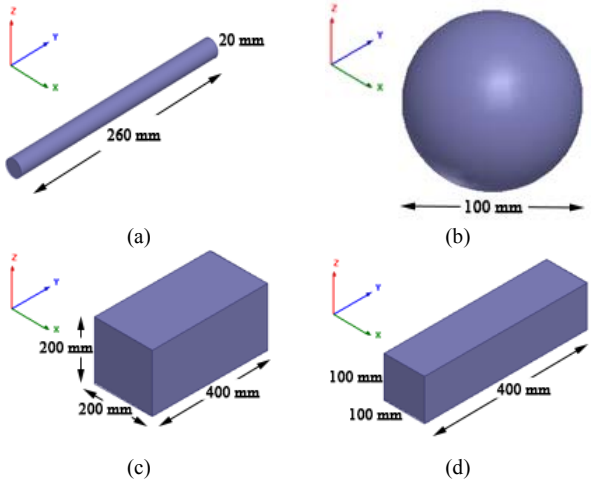
B. Tissue Models

The tissue models used to evaluate detuning effects upon ingestible antennas throughout their operation along the GI tract are shown in Fig. 2. The canonical models presented in this study can help the designer of an ingestible antenna to take into account the following issues:

- the differentiation of the surrounding tissue types and, therefore, dielectric properties which may drastically change the antenna performance and,
- the particular shape of each organ/tissue within which the ingestible antenna operates as it travels along the GI tract.

Antenna resonance, radiation, and safety performance issues are investigated while the antenna is being placed in four canonical models simulating the human esophagus, stomach, small and large intestine. The esophagus is being modeled by a circular cylinder 250 mm in length and 10 mm in radius (Fig 2(a)), the stomach by a sphere 50 mm in radius (Fig 2(b)), the small intestine by a box of 200 mm x 400 mm x 200 mm (Fig 2(c)) and the colon by a box of 100 mm x 100 mm x 400 mm (Fig 2(d)) [11], [12].

Single-tissue models are considered which accelerate simulations, while achieving acceptable accuracy within the initial design phase of the ingestible antenna [13], [14]. Moreover, permittivity (εr) and conductivity (σ) values at the frequency of 403.5 MHz are considered and approximated as constant within a ±100 MHz window [15]. Table I summarizes the dielectric properties of the tissues used in the simulations [8]. Maximum percent of deviations of the original relative permittivity (εr) and conductivity (σ) values within the simulation window from their values at 403.5 MHz are also given in Table I as $|\Delta\varepsilon_r|$ and $|\Delta\sigma|$ [%]. Results highlight the soundness of our decision to assume frequency-independent tissue properties inside a small frequency range. Mass densities of the tissues under consideration are also provided in Table 1.



(a) (b) (c) (d)

Fig. 2. The proposed canonical models for detuning effects assessment. (a) Esophagus, (b) Stomach, (c) Small Intestine, and (d) Large Intestine.

The ingestible antenna is assumed to be placed at different positions inside the proposed tissue models. The goal is to evaluate the effect of its relative positioning within each of the models upon its performance. For the esophagus, stomach, small and large intestine, three different positions have been examined (center of each model, 10 mm from the right and 10 mm from the left side/edge of each model in the Y-axis; center of X-Z plane).

C. Numerical Methods

FE numerical simulations are carried out in this study using the software HFSS [10]. The FE solver of HFSS performs iterative tetrahedron-meshing refinement automatically with the mesh being perturbed by 30% between each pass. The mesh refinement procedure has been set to stop when the maximum change in the reflection coefficient magnitude (|S11|) between two consecutive passes is less than 0.02, or when the number of passes exceeds 15. The solver performs an 800 point-frequency sweep by ±100MHz around the center frequency of MedRadio Band (403.5 MHz). Radiation boundaries are set $\lambda_0/4$ (λ_0 is the free space wavelength, f_0 = 403.5 MHz) away from all simulation set-ups to extend radiation infinitely far into space.

TABLE I
TISSUE PROPERTIES USED IN THE SIMULATIONS [8]

Tissue	ε_r	σ [S/m]	$\lvert\Delta\varepsilon_r\rvert$ [%]	$\lvert\Delta\sigma\rvert$ [%]	Mass Density [kg/m^3]
Esophagus	67.454	1.0041	3.194	1.863	1040
Stomach	67.454	1.0041	3.194	1.863	1050
Small Intestine	66.045	1.9044	3.350	5.636	1044
Large Intestine	62.529	0.85941	5.693	3.969	1044

III. Numerical Results and Discussion

A. Detuning Assessment

The reflection coefficient ($|S_{11}|$) frequency responses of the ingestible antenna at the center of each of the proposed tissue models are shown in Fig. 3. Table II shows the exhibited resonance, radiation and safety performance parameters when the ingestible antenna is placed at the center of each simplified tissue model. In Table II, Z_{in} represents the input impedance of the ingestible antenna at the center frequency of MedRadio band (403.5 MHz), bandwidth refers to 10 dB-bandwidth while max gain represents the maximum gain observed in dB. Finally, conformance with the latest IEEE standards [5] is assessed while applying numerical computational averaging procedures recommended by IEEE [16]. In order to guarantee conformance with the IEEE C.95.1-1999 and C.95.1-2005 the net-input power should not exceed the levels indicated in Table II as $P_{max,1999}$, $P_{max,2005}$ respectively. Finally, radiation performance of the antenna inside the four simplified models is presented in Fig. 4.

Detuning effects are observed among the four models, which are attributed to the differentiation of the shape of the model and its corresponding dielectric properties. For reference purposes, it is highlighted that the ingestible antenna was initially tuned inside a cubic muscle-model of the human trunk [9]. Detuning of the ingestible antenna appears to be more severe inside the canonical model of the small intestine. Given the fact that the permittivity value of the small intestine is close to that of the other tissues under consideration, the detuning effect can be attributed to the high conductivity value of the small intestine (nearly twice as high as the conductivity of the other tissues). As a result, the antenna exhibits very low reflection coefficient ($|S_{11}|$) values. However, under more realistic scenarios where multi-layer canonical models or anatomical models are to be used, the effect of the high conductivity of the small intestine is expected to fade due to the adjacent tissues (muscles, fat, skin etc.). In Fig. 5, insignificant detuning effects related to the differentiation of the position of the capsule inside each tissue model are observed for all scenarios under study.

Overall, the ingestible antenna performs as intended inside the esophagus model. However, the case is not the same with the stomach, small and large intestine. Nevertheless, the serpentine design of the ingestible antenna patch enables easy fine-tuning of the design for each tissue model under consideration. For example, slight design modifications need to be performed in order to tune the antenna inside the stomach and large intestine models. On the other hand, significant changes are required to fine-tune the antenna inside the model of the small intestine.

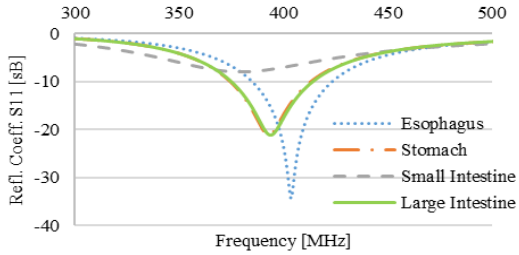


Fig. 3. Reflection Coefficient ($|S_{11}|$) frequency responses of the ingestible antenna when placed at the center of the four simplified models.

Even though a frequency shift to lower frequencies is observed in all scenarios except for esophagus (due to similar tissue properties used in antenna design [9]), the proposed antenna operates reasonably well in stomach and large intestine models due to its increased bandwidth. Ultimately, the design of an antenna which operates in all four simplified model is needed for WCE.

TABLE II
Resonance, Radiation and Safety Performance of the Ingestible Antenna for Different Scenarios

	Model			
	Esophagus	Stomach	Small Intestine	Large Intestine
$\lvert S_{11}\rvert$ [dB]	-34.37	-14. 48	-6.66	-14.37
Z_{in} [Ohms]	51.79 – j0.1	36.09 – j9.84	18.87 – j3.76	38.19 – j8.57
Bandwidth [MHz]	38.08	38.72	-	39.28
Max Gain (dB)	-24.725	-35.510	-57.168	-27.003
Max. SAR_{1g} [W/kg]	540.24	405.26	294.78	355.45
Max. SAR_{10g} [W/kg]	99.431	83.216	72.461	85.308
$P_{max,\ 1999}$ [mW]	2.961	3.948	5.427	4.501
$P_{max,\ 2005}$ [mW]	20.114	24.033	27.601	23.444

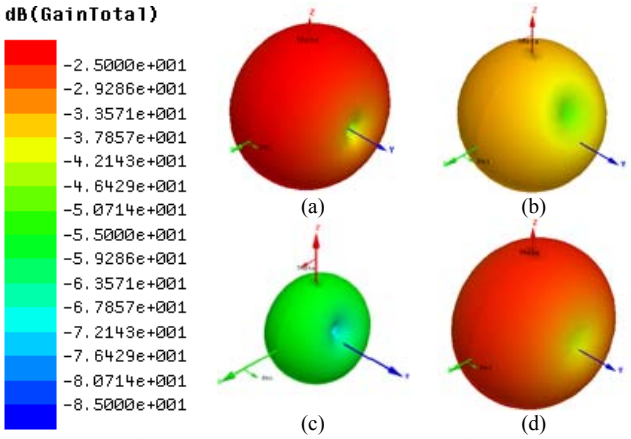


Fig. 4. Radiation performance of tuned ingestible antenna. 3D Radiation pattern while placed in the center of (a) esophagus, (b) stomach, (c) small intestine, and (d) large intestine

Until now, a simplified muscle tissue box has been reported in the literature as a model to evaluate the antenna performance inside the human body [4], [9]. The models

proposed in this work can provide a versatile and efficient tool to study antenna performance and related detuning effects inside the whole GI tract, within the initial steps of the design process. Thus, the use of anatomical models is limited resulting in a significant speed-up of the design procedure while valuable data are provided to final tune the antenna within the required standards for operation inside the GI tract.

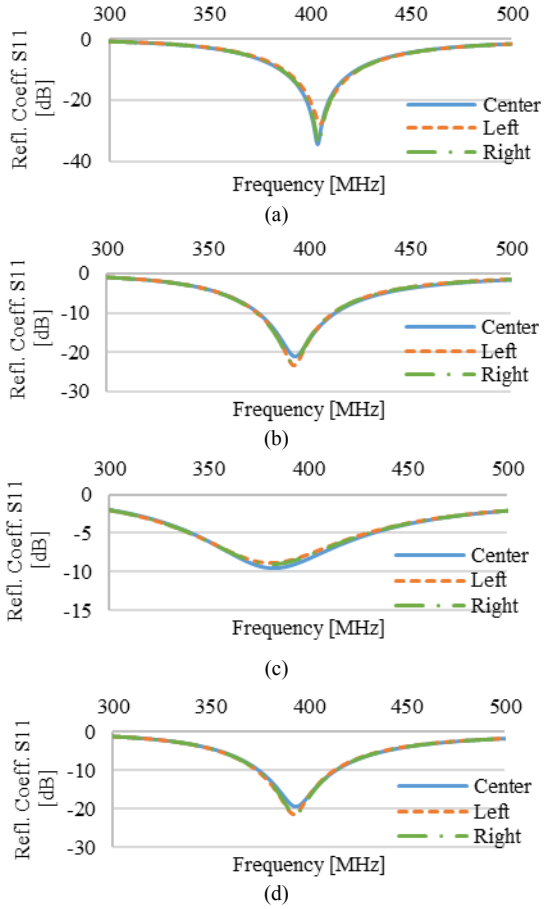


Fig. 5. Reflection Coefficient (|S11|) frequency response of the ingestible antenna for the different positions of the capsule inside (a) esophagus, (b) stomach, (c) small intestine, and (d) large intestine.

IV. Conclusions

In this study, an attempt to evaluate the detuning effects upon MedRadio ingestible antennas caused by the differentiation of the surrounding tissue environment as they move along the human GI tract, was presented. For this purpose, four canonical tissue models of the human esophagus, stomach, small and large intestine were proposed, which can prove useful within the first steps of ingestible antenna design and testing. The simplicity of the proposed models dramatically accelerates antenna design, as opposed to the use of anatomical models.

It is found that design of an ingestible antenna within a muscle-tissue model can be insufficient for scenarios in which the ingestible antenna is intended to operate within the small intestine. In this case, the antenna was shown to face significant detuning, as attributed to the differentiation of the tissue properties. On the other hand, detuning effects caused by the relative positioning of the ingestible antenna within the esophagus, stomach, small and large intestine were shown to be insignificant.

Future work will include antenna re-design and fine tuning in order to operate as intended in all four simplified models with sufficient performance needed for WCE application, as well as, experimental testing of the antenna and the proposed simplified models.

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