



Narrowband and Broadband Liquid Phantoms of Gastrointestinal Tissues

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Abstract

Wireless capsule endoscopy (WCE) has emerged as a promising alternative to traditional endoscopic procedures. However, these systems cannot be accurately assessed due to the lack of affordable and readily available gastrointestinal tissue phantoms. With the aim of overcoming this limitation, the current work presents tissue phantom recipes for oesophagus, stomach, small intestine and colon which cover some narrow (400 - 450 MHz, 900 - 950 MHz, 2.4 - 2.5 GHz and 5.7 - 5.9 GHz) and broad (0.4-3 GHz, 0.4-6 GHz and 3.1-10.75 GHz) frequency bands. The proposed recipes avoid the use of sugar, and are thus very stable over time.

1. Introduction

Wireless capsule endoscopy (WCE) represents a revolutionary approach to gastrointestinal (GI) imaging, offering a minimally invasive alternative to traditional endoscopic procedures [1]. Wireless capsule endoscopes are ingestible pill-sized devices equipped with cameras that capture images of the GI tract. These devices enable the examination of the different GI organs, reaching certain areas of the GI tract that are not accessible with wired endoscopy like the entire small intestine.

Wireless data transmission between in-body capsule endoscope and on-body receiver depends on antenna performance, making antenna design an essential part of WCE systems. In this way, different antennas have been developed for WCE in different frequency bands [1], [2]. The most used frequency bands for WCE are medical implantable communications service (MICS) which covers the range between 402 and 405 MHz, some industrial, scientific and medical (ISM) frequency bands such as 433.05-434.79 MHz, 902-928 MHz, 2.4-2.5 GHz and 5.725-5.875 GHz and, more recently, ultrawideband (UWB) frequency band ranging from 3.1 to 10.6 GHz.

Since WCE systems operate inside human body and human tissues presenting different dielectric properties that affect antenna performance, it is necessary to evaluate the system in presence of these biological media. To this aim, numerical models of biological tissues [3] can be used for antenna design in electromagnetic simulation software to mimic the human environment around the antenna. Once the antenna is designed, it is important to verify the results obtained through simulation using realistic measurement

models such as phantoms or live animals. Due to the fact that *in vivo* experiments with living animals are complex, and present many ethical constraints, tissue phantoms are a simpler and cheaper option.

Tissue phantoms are chemical compounds that mimic the dielectric properties of biological tissues and they can be solid, semisolid or liquid [4]. In the case of WCE systems, liquid phantoms are preferred because the ingestible device can be easily immersed in it. However, WCE systems are usually tested using muscle phantoms [5], [6], not considering the different tissues of the GI tract and restricting the accurate evaluation of WCE systems.

With the aim of improving WCE system testing, this work presents recipes that mimic oesophagus, stomach, small intestine and colon tissues for different narrow and broad frequency bands. The proposed phantoms are mixtures of Phosphate-Buffered Saline (PBS), distilled water, sodium chloride (NaCl) and Triton X-100 [7] and they cover some narrow (400 - 450 MHz, 900 - 950 MHz, 2.4 - 2.5 GHz and 5.7 - 5.9 GHz) and broad (0.4-3 GHz, 0.4-6 GHz and 3.1-10.75 GHz) frequency bands that are often used in WCE system. The proposed phantoms have a very good stability over time.

2. Measurement Setup

Open-ended coaxial probe is the most common method to measure the complex permittivity, equation (1), of biological tissues and liquid media because it is simple, it performs measurements in a broad range of frequencies and it allows minimal and non-destructive sample handling. The measurement system used in this work is shown in Figure 1 and it consists of a SPEAG DAK 3.5 open-ended coaxial probe connected to a HP-8720C VNA that is controlled from the computer using the software provided by SPEAG. The scanning range is set from 200 MHz to 20 GHz and the system calibration is performed using air, distilled water at room temperature (21°C) and a short termination.

To ensure the reliability of the measurements, the accuracy of the systems is assessed using 0.1M NaCl solution and following guidelines in IEEE Standard 1528™ [8]. The obtained uncertainty values for the dielectric constant, $\epsilon'(\omega)$, and loss factor, $\epsilon''(\omega)$, of the complex permittivity are presented in Table 1. As the obtained uncertainty values are low, it can be considered that the system is accurate.

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) = \varepsilon'(\omega) - j\frac{\sigma(\omega)}{\omega\varepsilon_0} \quad (1)$$

Table 1. System Uncertainty.

Frequency Range	Uncertainty	
	ε'	ε''
200 MHz – 10GHz	0.32%	3.62%
10 GHz – 20 GHz	0.95%	0.67%

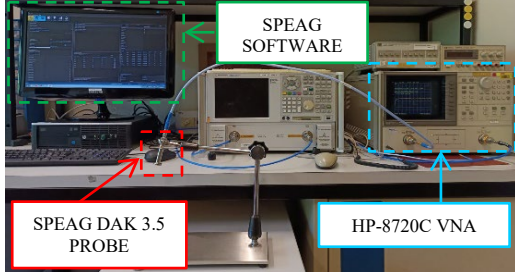


Figure 2. Measurement setup.

3. Phantom Compounds and Preparation

The liquid phantoms proposed in this work are mixtures of PBS, distilled water, sodium chloride and Triton X-100 non-ionic surfactant [7]. PBS is used as base component because it presents similar dielectric properties to those of biological tissues [9], has a simple composition, is cheap and is easy to obtain. The other ingredients are added to modify the dielectric properties of the base components in a specific manner. Distilled water increases the dielectric constant, sodium chloride rises the loss factor and Triton X-100 decreases the dielectric constant and loss factor. Therefore, the dielectric properties of oesophagus, stomach, small intestine and colon at different frequency bands can be reached by mixing the proper amounts of the base component and the other ingredients. Because temperature affects the dielectric properties of the employed materials, the phantoms presented in this work are measured at room temperature (21°C).

Due to the high viscosity of Triton X-100 a specific procedure needs to be followed to prepare the different mixtures [4]:

1. Add the different proportions of PBS, NaCl and distilled water and stir the solution with a magnetic bar until sodium chloride is dissolved.
2. Add the required quantity of Triton X-100 to the obtained solution. Then, immerse the mixture in a 45°C water bath and stir with a magnetic bar until obtaining a homogeneous mixture.
3. Once the solution is homogeneous, bring it to room temperature (or any wished temperature).

4. Phantom Recipes and Measurements

Considering the effect of each compound and following the preparation procedure explained previously, several mixtures with different proportions of the mentioned

compounds have been made and measured. As a result, diverse gastrointestinal tissue phantoms covering narrow and broad frequency bands have been obtained.

Narrowband phantoms are designed in the frequency bands 400 - 450 MHz, 900 - 950 MHz, 2.4 - 2.5 GHz and 5.7 - 5.9 GHz, which covers MICS frequency band and some ISM frequency bands (433.05-434.79 MHz, 902-928 MHz, 2.4-2.5 GHz and 5.725-5.875 GHz). In the case of broadband phantoms, they are designed in the frequency ranges 0.4-3 GHz, 0.4-6 GHz and 3.1-10.75 GHz which covers the MICS frequency band, some ISM bands and the UWB band. The recipes for oesophagus, stomach, small intestine and colon tissue phantoms for the cited frequency bands are presented in Table 2. The measured permittivity of the proposed tissue phantoms compared to their Cole-Cole models [3] are shown in Figure 2 and Figure 3. Regarding the obtained measurements, a good agreement between tissue models and the prepared phantoms is obtained.

With the aim of quantifying the accuracy of the proposed phantoms compared to their Cole-Cole models, three different error estimators are used: combined error (e_c) [7] and relative error (e_{r-real} and e_{r-imag}). The mathematical expression of combined error is shown in (2), where:

- $\varepsilon'_t(\omega_i)$ and $\varepsilon''_t(\omega_i)$ are the dielectric constant and loss factor of the target tissue Cole-Cole model at i frequency.
- $\varepsilon'_p(\omega_i)$ and $\varepsilon''_p(\omega_i)$ are the dielectric constant and loss factor of the measured phantom at i frequency.
- N indicates the number of frequency points used in the measurements.

$$e_c = \sqrt{\frac{\sum_{i=1}^N \left[\left(\frac{\varepsilon'_t(\omega_i) - \varepsilon'_p(\omega_i)}{\varepsilon'_t(\omega_i)} \right)^2 + \left(\frac{\varepsilon''_t(\omega_i) - \varepsilon''_p(\omega_i)}{\varepsilon''_t(\omega_i)} \right)^2 \right]}{N}} \quad (2)$$

While relative error estimator provides accuracy values for the dielectric constant and loss factor independently, combined error considers the real and imaginary parts of the permittivity at the same time and provides a global overview of the phantom.

The calculated error values for oesophagus, stomach, small intestine and colon tissue phantoms are shown in Table 3. In general, the proposed phantoms show relative and combine errors smaller than 10% for all the tissues in all proposed frequency bands, indicating that the prepared phantoms are accurate [7]. Moreover, the errors and deviations obtained for the imaginary part are larger than the ones computed for the real part, showing that is more difficult to match the loss factor than the dielectric constant. The measurements of the gastrointestinal phantoms presented in this work are available in an open access repository [10] along with other recipes and measurements for other tissue phantoms based on PBS, distilled water, salt and Triton X-100.

Table 2. Recipes of gastrointestinal tissue phantoms for different frequency bands and their accuracy.

		Phantom Composition (%)				Phantom Accuracy		
		PBS	Triton X-100	Sodium Chloride	Distilled Water	ϵ_c (%)	ϵ_{r-real} (%)	ϵ_{r-imag} (%)
Oesophagus	400 - 450 MHz	22.79	15.19	0.29	61.73	4.71	0.80	4.29
	900 - 950 MHz	22.79	15.19	0.29	61.73	5.09	0.18	5.07
	2.4 - 2.5 GHz	22.81	15.21	0.19	61.79	1.84	1.31	1.28
	5.7 - 5.8 GHz	22.86	15.24	-	61.90	5.45	5.35	0.96
	3.1 - 10.75 GHz	22.86	15.24	-	61.90	6.02	4.39	2.65
	0.4 - 3 GHz	22.79	15.19	0.29	61.73	4.76	0.68	4.43
	0.4 - 6 GHz	22.79	15.19	0.29	61.73	9.14	1.98	7.87
Stomach	400 - 450 MHz	22.77	15.18	0.38	61.67	9.78	2.99	9.31
	900 - 950 MHz	22.77	15.18	0.38	61.67	7.57	1.99	7.30
	2.4 - 2.5 GHz	22.81	15.21	0.19	61.79	2.22	1.72	1.39
	5.7 - 5.8 GHz	22.86	15.24	-	61.90	6.34	5.91	2.19
	3.1 - 10.75 GHz	22.86	15.24	-	61.90	6.92	5.35	3.31
	0.4 - 3 GHz	22.77	15.18	0.38	61.67	6.04	1.95	5.13
	0.4 - 6 GHz	22.77	15.18	0.38	61.67	9.60	2.94	8.29
Small intestine	400 - 450 MHz	79.50	19.88	0.62	-	12.59	8.71	9.02
	900 - 950 MHz	79.50	19.88	0.62	-	9.37	1.51	9.25
	2.4 - 2.5 GHz	79.60	19.90	0.50	-	1.94	0.45	1.89
	5.7 - 5.8 GHz	75.12	18.78	0.23	5.87	0.89	0.87	0.13
	3.1 - 10.75 GHz	75.12	18.78	0.23	5.87	4.31	2.71	2.62
	0.4 - 3 GHz	79.50	19.88	0.62	-	6.73	1.18	5.10
	0.4 - 6 GHz	79.50	19.88	0.62	-	7.94	1.45	6.75
Colon	400 - 450 MHz	26.64	17.76	0.11	55.49	1.33	0.90	0.65
	900 - 950 MHz	29.94	19.96	0.20	49.90	3.97	3.24	2.27
	2.4 - 2.5 GHz	34.29	22.86	-	42.85	2.96	0.42	2.94
	5.7 - 5.8 GHz	30	20	-	50	9.24	1.23	9.15
	3.1 - 10.75 GHz	30	20	-	50	8.12	1.65	7.38
	0.4 - 3 GHz	29.94	19.96	0.20	49.90	9.25	3.59	6.72
	0.4 - 6 GHz	36.84	24.56	0.23	38.37	13.51	5.14	11.46

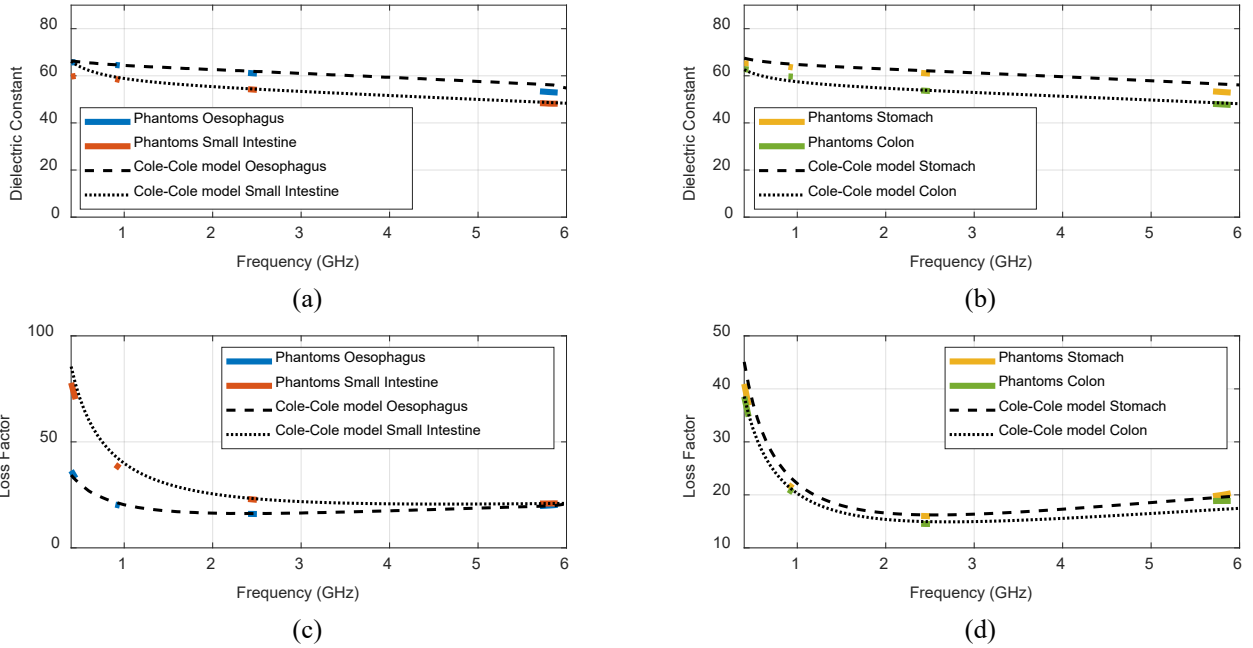


Figure 2. Dielectric constant (a) (b) and loss factor (c) (d) of gastrointestinal Cole-Cole tissue models and their narrowband phantoms.

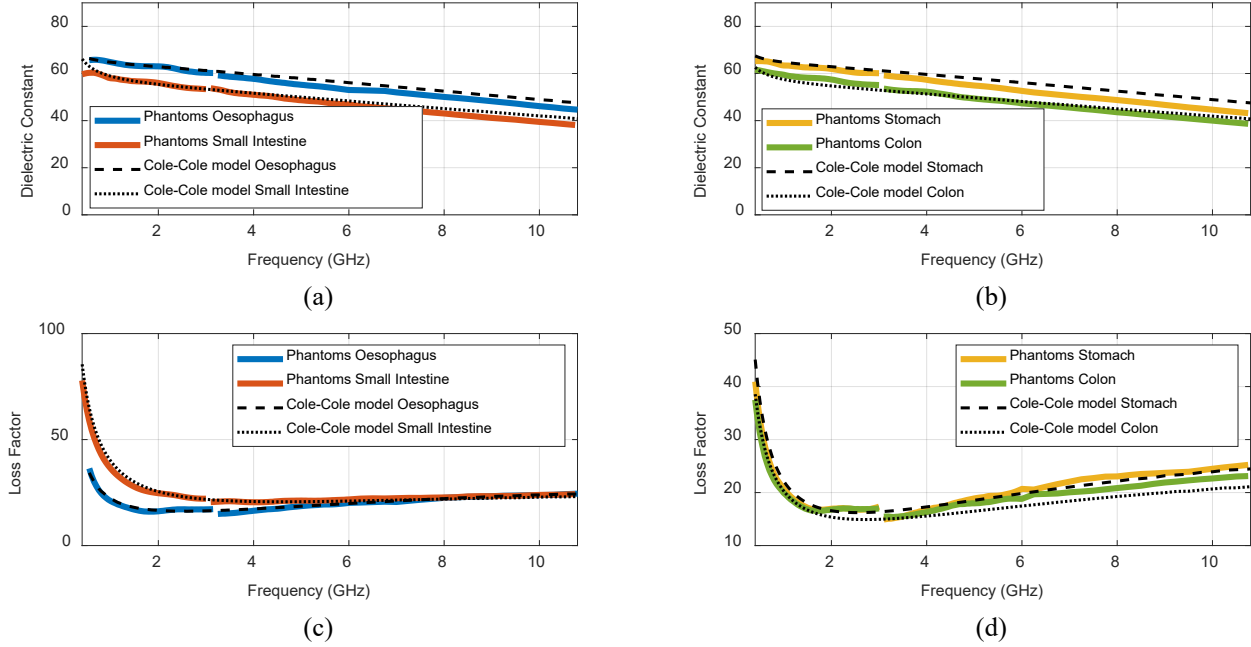


Figure 3. Dielectric constant (a) (b) and loss factor (c) (d) of gastrointestinal Cole-Cole tissue models and their 0.4-3 GHz and 3.1-10.75 GHz broadband phantoms.

5. Conclusions

Recipes for liquid phantoms of oesophagus, stomach, small intestine and colon at different narrow and broad frequency ranges have been presented. These phantoms are mixtures of PBS, distilled water, sodium chloride and Triton X-100 at 21°C. Furthermore, low error values have been obtained between the measured phantoms and their theoretical models, meaning that the proposed phantoms mimics quite accurately the dielectric properties of the target tissues.

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