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Dielectric Characterization of *In Vivo* Abdominal and Thoracic Tissues in the 0.5–26.5 GHz Frequency Band for Wireless Body Area Networks

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ABSTRACT The dielectric properties of biological tissues are of utmost importance in the development of wireless body area networks (WBANs), especially for implanted devices. The early design stages of medical devices like capsule endoscopy, pacemakers, or physiological sensors rely on precise knowledge of the dielectric properties of the tissues present in their surrounding medium. Many of these applications make use of electromagnetic phantoms, which are software or physical models that imitate the shape and the electromagnetic properties of the tissues. They are used for designing devices in software simulations and for testing them in laboratory trials, aiding in both the development of WBAN antennas or in communication link evaluations. The existing reports about dielectric *in vivo* properties are limited and have drawbacks like: low variety of characterized tissues, lacking some relevant ones, and limitations and inhomogeneity in the measured frequency range. This paper aims at filling that gap by providing a new database of dielectric properties of biological tissues measured *in vivo*. In particular, it is focused on the tissues of the thoracic and the abdominal regions, measured at the same wide frequency band, on the same animal specimen, and under the same conditions. The properties have been obtained by measuring porcine tissues in the 0.5–26.5 GHz band with the open-ended coaxial technique. In this paper, we focus on those tissues that have been scarcely characterized so far in the literature, like heart, esophagus, stomach, and pancreas. The Cole–Cole fitting parameters of the measured tissues and their uncertainties are provided.

INDEX TERMS Biological materials, body sensor networks, dielectric measurement, in vivo, permittivity.

I. INTRODUCTION

Nowadays, the development of Wireless Body Area Networks (WBAN) keeps growing steadily. Most WBAN applications are developed for the healthcare domain, although this technology is used in sports, military and security fields as well. A typical WBAN is composed of one or some wireless sensor nodes, either attached to the human body or implanted into it, and a control unit that receives the data collected by them, usually located outside the human body. In general, these networks operate in the Medical Implant Communication System (MICS) or Industrial, Scientific and Medical (ISM) bands such as 402-405 MHz, 902-928 MHz or 2.4-2.485 GHz, although other bands like ultra-wideband (UWB) or higher ISM bands are candidates as well.

The design of WBAN systems and devices requires an accurate knowledge of the electromagnetic properties of biological tissues, since the latter are a core part of the

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communication channel in WBAN [1]. The knowledge of these properties is essential for developing capsule endoscope systems or implanted medical devices, especially if they are intended to work in higher frequency bands. The latter includes stimulatory devices like cochlea implants, pacemakers, neurostimulators, and implantable cardioverter defibrillators, and measurement or monitoring devices such as diagnostic sensors or drug infusion [2]. For instance, the antennas performance of these systems are heavily affected if they are in contact or very close to a human body in terms of radiation patterns and matching [3], and the channel can vary heavily depending on the distance and the tissues that the electromagnetic signals pass through.

The dielectric properties of the biological tissues are needed for making electromagnetic phantoms, which are tools that aid in the development of some of the aforementioned networks, either for designing or testing purposes. They are very helpful to evaluate the electromagnetic interaction of the biological tissues over the WBAN system or device under development. On the one hand, there are software phantoms, which are CAD, voxel or geometry models used in software simulations [4]. They imitate the shape and the dielectric properties of the biological tissues. On the other hand, there are physical phantoms, which have the same objective but once the device is manufactured or the system deployed. The latter phantoms can be either liquids, solids or gels, and mimic the electromagnetic properties of specific human tissues for specific frequency bands.

The research of the dielectric properties of biological tissues has grown consistently since the early years of the past century [5]. This interest has provided great contributions to the biophysical and physiological sciences [6], and has led to a rapid growth of the electromagnetic characterization techniques. There are many works in the literature addressing the dielectric properties of most of the biological tissues. Generally, these studies were performed on animals in diverse conditions (*in vivo*, *in vitro,* and mainly *ex vivo*), but there are also a fewer number of studies carried out on humans. Despite the many published works, the database from [7] is broadly used as reference. The main reasons to use this work are the huge catalogue of tissues offered and the large frequency bandwidth measured, from 1 MHz or below and up to 20 GHz. However, since most tissues were measured in *ex vivo* conditions, the actual *in vivo* values are expected to be slightly higher mainly due to the potential dehydration after death [8].

Regarding the published *in vivo* studies, some drawbacks can be highlighted. Firstly, the previous works are focused on a few tissues or organs, amongst which skin [7], [9]–[12], grey matter [13]–[17], kidney [13]–[15], liver [14]–[16], [18]–[20], muscle [11], [13]–[16], and spleen [14]–[16] are the most portrayed ones. On the contrary, without any apparent reason, other tissues such as esophagus and pancreas have not been measured at all above 500 MHz. In addition, there is a heterogeneity regarding the animal species chosen for characterization: there are works performed on cats [14], dogs [13], frogs [11], humans [7], mice [21], pigs [22], rats [16], and sheep [10], among others. This can lead to inconsistencies when comparing analogous or different tissues from different species. Another important problem is the diversity of frequencies at which the studies were performed. On one hand, some authors measured from frequencies below the kilohertz range [7], whereas others started from hundreds of megahertz [19]. On the other hand, some authors measured up to a few gigahertz [15], whereas others characterized up to millimeter-waves [18].

The main goal of the work presented in this paper is providing a new database of dielectric properties of biological tissues, focusing on the tissues of the thoracic and the abdominal region. The design stages of many WBAN applications such as capsule endoscopy, pacemakers or physiological sensors can make use of this data, especially if they are intended to work in frequency bands larger than the current commercial systems. The main novelty of the database lies in the great number of *in vivo* tissues, all of them characterized for the same large frequency band, on the same animal species, and under the same conditions. To gather all this data, laparotomy and thoracotomy procedures have been performed on sedated porcine specimens whose tissues have been measured using the open-ended coaxial technique, for the frequency band between 0.5 and 26.5 GHz. All the results have been fitted to a Cole-Cole model to make them easily available to the scientific community. In this paper, we also discuss in greater detail those tissues which have been barely studied *in vivo* so far in literature, such as heart, esophagus, stomach, and pancreas.

The remainder of this paper is organized as follows: in Section II, the procedure of animal surgery and measurement methodology are described. In Section III, the results for the *in vivo* measurements are presented and their uncertainties detailed. Results are discussed in Section IV, and finally, conclusions are drawn in Section V.

II. METHODS

The permittivity of a medium describes its tendency to be polarized when an electromagnetic field is applied. In terms of electromagnetic behavior, the permittivity allows to assess how much energy can be stored in the medium and the velocity of propagation of an electromagnetic signal that travels through it [23]. It is a complex, frequency-dependent property which is usually presented in relative terms, normalizing its values to those of the vacuum as:

$$\varepsilon_r^*(f) = \frac{\varepsilon^*}{\varepsilon_0} = \varepsilon_r'(f) - j\varepsilon_r''(f) \tag{1}$$

where ε_r^* is the resulting complex relative permittivity, ε^* (F/m) is the complex absolute permittivity, ε_0(F/m) is the permittivity of the vacuum, f is the frequency (Hz), ε_r' is the real part of the relative permittivity, commonly known as dielectric constant, and ε_r'' is the imaginary part of the relative permittivity, also known as loss factor.

A. SURGICAL PROCEDURE

The experiment described in this section was approved by the ethical committee of animal experimentation of the Hospital Universitari i Politècnic La Fe, València, Spain, and approved as well by the ethical committee of the regional authority (GVA). The experiment was in accordance with the animal-care guidelines set forth by the national government and the European Commission. Three female porcine specimens of around 50 kilograms were selected as animal subjects for this study because of the anatomy resemblance of its organs with the human ones [24], [25]. Apart from the available tissues, no significant electromagnetic differences are expected between using male and female specimens, since among all the available studies there is barely any reference regarding this fact. Measurements were conducted in an operating surgery room equipped for animal experimentation of the La Fe Research Foundation. The room was kept at constant temperature of 21 °C degrees during the three procedures. In each of them, the subject was sedated and anesthetized before the surgery, anesthesia that was maintained during the surgery. The animal model was subjected to a continuous intravenous infusion of fentanyl and lactated Ringer as well. Its heart rate, blood pressure, respiratory frequency, and palpebral reflex were monitored continuously to correct possible shortage or excess in anesthesia, if needed.

The surgery consisted firstly in a laparotomy, which is a surgical procedure to open the abdominal cavity. The laparotomy itself is performed in just a few minutes, and right after we could start with the measurements since all the tissues of the abdominal region were accessible. The laparotomy of the animal subject can be seen in Fig. 1. Once the tissues of the abdominal region were measured, a left thoracotomy was done to access and measure the tissues of the thoracic cavity. The temperature of the characterized tissues varied between 37.2 °C and 38.5 °C, which is slightly lower than the normal body temperature of the animal due to the anesthesia and the fact that the abdominal and thoracic cavities were opened.

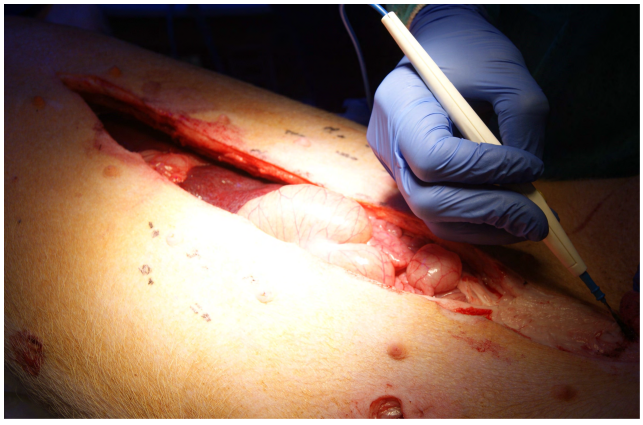

FIGURE 1. Photograph of the laparotomy performed on the animal subject.

B. MEASUREMENT SYSTEM AND DATA ACQUISITION

In this work, we have chosen the open-ended coaxial technique for measuring the dielectric properties of biological tissues. This technique has been the most used one for performing these kinds of measurements due to its many advantages: it is a simple, non-destructive method, with a wide frequency bandwidth, and suitable for measuring semi-solid materials [26], [27]. In our particular case, the system consists of a Vector Network Analyzer (Keysight© Fieldfox N9918A, hereinafter referred to as VNA), an open-ended coaxial probe (Keysight© N1501A slim form probe, 2.2 mm outer diameter), a coaxial cable, and a computer. The system is based on measuring and processing the reflection that appears due to the change of medium between the coaxial probe and the material under test.

A calibration of the system before performing any measurement is mandatory. This procedure translates the measurement plane from the VNA port to the open-ended coaxial end, minimizing the effect that the hardware elements introduce to the performance of the system and relating a reflection measurement with its corresponding dielectric properties. In this study, we performed the calibration as described in [28], which is based in a previous measurement of the reflection coefficients of media with well-known permittivity (open circuit, short circuit, deionized water, and methanol). These calibrators have been proved to enhance the performance of the system for measuring the permittivity of biological tissues. In particular, our system was configured to work in the 0.5 –26.5 GHz frequency band, with an output power of −10 dBm, 1 kHz of IF bandwidth, and 401 linearly spaced frequency points. We made 3 different calibrations to reduce random errors, and thus, the uncertainty. A 0.1 M saline solution was measured to check visually the validity of these calibrations, comparing the measurements obtained using them with the data provided in [29]).

Then, we characterized 3 times in at least 5 different points for each tissue and animal, having thus a minimum of $3 \times 15 = 45$ measurements per tissue. To this end, the probe was moved manually from the calibration position to the measurement ones, holding it against the tissues and trying to keep the curvature of the coaxial that connects it with the VNA. Since a coaxial cable with high phase stability against bending was used, measurements are barely affected by this factor, as will be shown later in Section II-C. The system was recalibrated after characterizing two different tissues, and less than 10 minutes were needed to measure two of them.

Because of the dimensions of the probe used, the penetration depth of the measurements is always below 5 mm for any measured permittivity and frequency of the analyzed bandwidth. This depth has been studied in [30] and [31] for several frequencies and permittivities, returning penetration depths of around 2 mm for the same probe dimensions used in this research. Besides, these measurements are not affected by the nearby tissues if the width of the samples has a diameter larger than two millimeters [32]. Hence, the volume delimited by these distances was respected in order to ensure

the validity of the measurements, not being a problem since tissues were large enough. On the other hand, enough force had to be applied from the probe to the tissues in order to avoid the presence of air bubbles, but preventing any fluid accumulation at the probe tip or tissue damage that could compromise the measurements [27].

C. SYSYEM UNCERTAINTY

The uncertainty of the open-ended coaxial system used, along with its calibration procedure, was assessed in a similar way as in [33]. We followed their procedure since it agrees with the guidelines presented in [34] and [35] and they identified the uncertainty sources that this kind of systems has. There are four sources of uncertainty:

1) Repeatability. Related to random errors, it was assessed by computing the Standard Deviation of the Mean (SDM) of repeated measurements of 3 homogeneous samples of 0.1 M NaCl solution, measured in different sessions and re-calibrating in each of them.
2) Systematic errors due to the instrumentation and measurement methodology. They were evaluated calculating the deviation of the mean measurements of the previous saline solution from the literature values presented in [41].
3) Drift of system with time. It was evaluated by computing the difference between some measurements of the saline solution just after a calibration and further measurements performed 15 minutes later. This time was chosen because the system was expected to be recalibrated in the *in vivo* experiment regularly. Besides, the VNA was turned on 3 hours before the trials and the *in vivo* experiment to avoid the drifting related to its warming up.
4) Movement of the coaxial cable that connects the VNA to the open-ended coaxial sensor. It was quantified by performing measurements of the NaCl solution emulating similar cable movements to those that it was expected to suffer in the *in vivo* experiment.

The uncertainties of these sources were quantified prior to the *in vivo* experiments, in laboratory conditions at a temperature of 20 °C. The values calculated for each source are shown in Table 1, for three different frequency regions.

TABLE 1. Values of system uncertainty in percentage terms of the relevant parameter for 3 frequency regions.

Frequency region	Parameter	(1)	(2)	(3)	(4)	Combined Uncertainty
0.5 – 10 GHz	ε_r'	0.61	0.40	0.05	0.21	0.67
	ε_r''	0.71	0.66	0.12	0.42	0.86
10 – 18 GHz	ε_r'	0.47	0.36	0.10	0.41	0.59
	ε_r''	0.46	2.19	0.28	1.96	1.94
18 – 26.5 GHz	ε_r'	1.84	0.78	0.20	0.95	2.01
	ε_r''	1.94	3.09	0.42	3.51	3.63

System uncertainty is higher for loss factor than for dielectric constant, and in general it increases with frequency, as also occurs in [33]. This can be explained by the fact that loss factor is more sensitive to small errors in the reflection measurements than the dielectric constant. The combined system uncertainty is computed as presented in [33], as the square root of the sum of the squares of each source, taking into account as well the probability distribution of their errors in its calculation. It should be highlighted that the repeatability source found in this section is particular for the saline solution considered for assessing the uncertainty of the measurement system, and does not have the same values when characterizing tissues.

D. DATA PROCESSING

Once all the measurements of the characterized tissues have been gathered, their mean permittivities are computed. Then, the combined uncertainty of each of the average permittivities is assessed considering the same sources of uncertainty than in the previous section. The sources 2, 3, and 4 (i.e., instrumentation and measurement methodology, drift of system with time, and movement of the coaxial cable) are common regardless the tissue analyzed, but the repeatability differs for each one of them. The SDM of the permittivities measured of each tissue is used as their respective repeatabilities, as in [33]. The total uncertainty of the mean permittivity of each tissue is computed for each measured frequency by combining the different sources in the same manner as in the previous section.

Lastly, the mean permittivity of each tissue is fitted to a 2-pole Cole-Cole equation. This equation is used in order to make the permittivity easily accessible to the rest of the scientific community, as usually done in related works [36], [37]. The Cole-Cole equation is given by the equation:

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \sum_{m=1}^{M} \frac{\Delta\varepsilon_m}{1 + (j\omega\tau_m)^{(1-\alpha_m)}} + \frac{\sigma_s}{j\omega\varepsilon_0} \qquad (2)$$

where M is the number of fitting poles of the equation, ε_0(F/m) is the permittivity of the vacuum, ω is the angular frequency ($2\pi f$), and ε_∞, $\Delta\varepsilon_m$, τ_m(s), α_m, and σ_s(S/m) are the fitting coefficients of equation (3). Each pole of the equation describes the effect of a particular dispersion region, which are spectrum regions in which the permittivity of biological tissues varies strongly with frequency [38]. Results are fitted considering only 2 poles of the Cole-Cole equation since only two dispersion regions have an effect in the measured frequency bandwidth. Coefficients are computed in MATLAB by minimizing the sum of squares and using the trust-region-reflective method, which is based on trust regions [39], [40].

III. RESULTS AND COMPARISON WITH PREVIOUS STUDIES

The more innovative results are commented in Section III-A. Besides, for each characterized tissue, the Cole-Cole fitted parameters of their mean permittivities are provided in Section III-B, the uncertainties of these means are given and

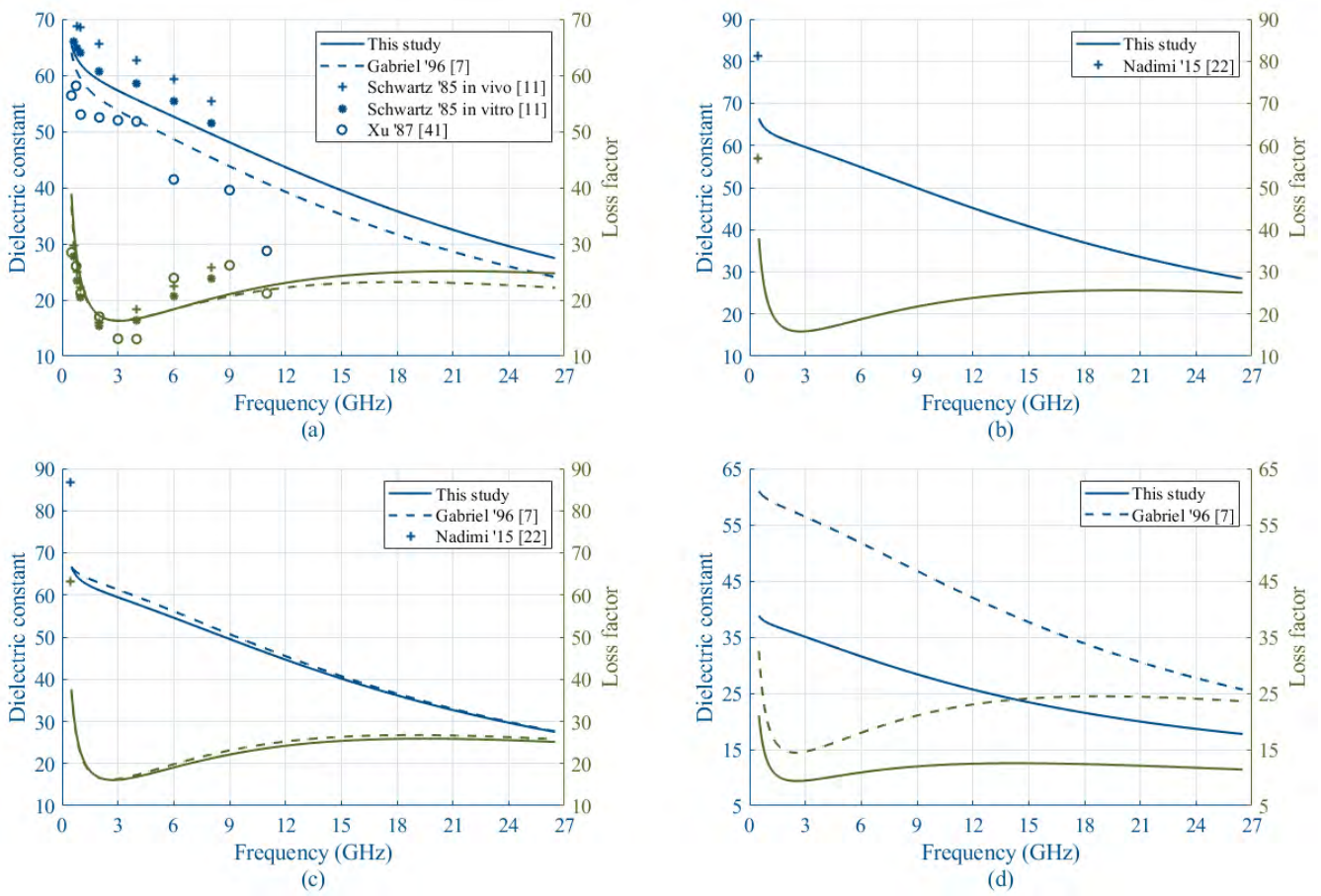

FIGURE 2. Averaged dielectric constant (blue) and loss factor (green) of (a) heart, (b) esophagus, (c) stomach, and (d) pancreas compared to other studies.

discussed in Section III-C, and the differences with previous studies are summarized in Section III-D.

A. HIGHLIGHTED RESULTS

In this section, we provide a particular analysis of heart, esophagus, stomach, and pancreas tissues given the scarcity of dielectric studies in literature about them in contrast to the rest of tissues. The dielectric properties of each one of these tissues are presented in a single chart, along with the data reported in other studies for them.

The *in vivo* permittivity of heart tissue is presented in Fig. 2(a). Previous *in vivo* results are available for the 0.2 – 8 GHz band in [11]. The data presented in our paper showed lower values in comparison to this study, which may be due to the fact that they measured *in vivo* frog heart at 22 °C whereas our measurements were carried out at 38.5 °C, much closer to normal human body temperature. They also measured heart tissue *in vitro* at 22 °C, decreasing the values but being still slightly higher than ours. Heart properties have been characterized *ex vivo* in Gabriel's database [7] and in [41], having lower properties than our study as it can be seen in Fig. 2(a).

Esophagus and stomach dielectric data are depicted in Figs. 2(b) and 2(c), respectively. With regard to literature, *in vivo* measurements of these tissues were only found for the 433 - 434 MHz band in [22]. Their esophagus data seem to correlate well with ours, although this is difficult to state because of the effect of the previous dispersion region. This dispersion greatly increases the slope of the dielectric constant within the frequencies in which their results are presented, causing much higher dielectric constant values below 500 MHz. On the other hand, their stomach values seem to be differ with ours to a higher degree. The body temperature of their specimen was not reported, so we cannot assess whether it caused this greater discrepancy or not. Given the similarities with our setup, significant differences in temperature are not expected. Besides, measurements of cancerous stomach tissue were performed from 500 MHz to 5 GHz in [17]. However, we cannot compare our results with this work since cancerous samples have in general higher permittivity values [42], [43]. Regarding *ex vivo* results, Gabriel's properties for stomach are almost identical to those presented in our study.

Lastly, pancreas data are depicted in Fig. 2(d). The uncertainties found for both parts of the permittivity are much higher than for most of the characterized tissues, as will be shown later in Table 3. A similar degree of uncertainty is already known for other tissues such as skin, fat, and lung [7], although it has not been addressed for pancreas

TABLE 2. 2-Pole cole-cole fitting coefficients for the measured tissues and fitting error.

Tissue	ε_∞	$\Delta\varepsilon_1$	τ_1 (ps)	α_1	$\Delta\varepsilon_2$	τ_2 (ns)	α_2	σ_s (S/m)	Fitting error (%) ε_r' | ε_r"
Aorta	1.000	43.250	9.141	0.098	1360.509	439.155	0.377	0.291	1.535 | 2.140
Bladder	2.008	56.689	8.203	0.051	866.641	223.742	0.387	0.659	1.113 | 1.688
Blood	7.500	53.673	8.967	0.170	632.735	5.443	0.003	0.027	2.277 | 3.490
Colon	5.575	57.408	7.500	0.142	1617.041	21.050	0.049	0.240	0.769 | 2.954
Esophagus	3.492	58.771	7.390	0.113	934.202	9.932	0.057	0.001	0.729 | 1.296
Fallopian tubes	2.022	53.699	7.229	0.007	391.079	17.225	0.267	0.496	1.371 | 2.206
Fat	5.587	8.293	13.500	0.042	5.011	0.435	0.094	0.139	1.782 | 3.577
Gallbladder	2.849	55.061	7.167	0.072	264.682	23.525	0.312	0.730	0.937 | 1.691
Heart	2.511	54.178	6.914	0.096	1161.477	439.155	0.400	0.701	0.997 | 1.565
Kidney	4.850	51.691	8.149	0.122	452.493	11.421	0.136	0.353	0.719 | 1.157
Liver	6.639	47.545	10.329	0.126	8.939	0.375	0.000	0.587	0.597 | 0.843
Lung	6.373	23.958	8.569	0.168	2000.000	58.952	0.066	0.089	1.255 | 2.435
Muscle	2.504	57.810	8.079	0.138	660.060	7.840	0.064	0.103	0.619 | 1.052
Ovary	7.500	50.358	8.718	0.124	192.885	2.257	0.001	0.029	1.094 | 1.697
Pancreas	7.500	30.676	10.045	0.160	247.513	4.687	0.000	0.076	1.791 | 3.535
Skin	2.843	40.665	7.725	0.229	135.310	3.072	0.053	0.129	0.628 | 1.204
Small intestine	6.097	57.200	7.777	0.152	997.973	17.630	0.069	0.425	1.364 | 2.806
Spleen	7.500	51.454	9.275	0.181	327.594	3.918	0.004	0.100	2.104 | 3.619
Stomach	4.045	57.239	7.641	0.095	448.590	12.308	0.155	0.454	0.696 | 2.826
Uterine matrix	1.000	55.043	8.534	0.029	2000.000	407.500	0.351	0.417	2.041 | 2.673

tissue until this work. Regarding *in vivo* measurements of this tissue, no references were found in literature. Although in [44] *ex vivo* properties are presented, their values are too high compared to ours. To the best of our knowledge, this may be caused by their assumption that pancreas tissue has the same dielectric properties as the thyroid (which was originally measured in [7]).

Besides, since the uncertainty that we obtained for pancreas was so large and the differences with [44] were abnormal, we checked our results by measuring in additional positions of this particular tissue (a total of 105 measurements of this tissue were performed instead of 45, like with the rest). In addition, we characterized this tissue also in *ex vivo* conditions, in which we observed that this large uncertainty, although lower than *in vivo*, was still present and then was not only caused by blood perfusion. It may be due to a large natural inhomogeneity of this particular tissue, as exposed in [33] for explaining the SDM of the biological tissues. Further studies should conduct the histological analysis of the measured pancreas samples in order to give a deeper insight with regard to this matter.

B. COLE-COLE FITTING

The 2-pole Cole-Cole coefficients for the average permittivity of all the characterized tissues are presented in Table 2. The first pole describes the γ-dispersion, related to the relaxation frequency of water and, hence, to the water content of tissues [38]. It is the most significant dispersion within the measured bandwidth, and its most characteristic parameter is $\Delta\varepsilon_1$. The higher this coefficient, the higher the permittivity at the lower frequencies of this pole and the higher the water content of a tissue. For instance, high water-content tissues like those from the gastrointestinal tract (i.e., colon, esophagus, small intestine, and stomach) have larger values than those with lower water content, such as lung, skin or fat. The other two terms of the pole, τ_1(s) and α_1, define the trend of the permittivity curve within the dispersion region.

It is important to remark that the found coefficients of the second pole, which is the one with the lower relaxation frequency, have less physical significance since we have not measured a great part of the dispersion region in which it affects. The same consideration applies to the found values of the coefficient ε_∞, related to the permittivity when frequency tends to infinite, since we are not measuring at high enough frequencies.

Some authors that measured almost the same frequency band perform the Cole-Cole fitting considering only the pole related to the γ-dispersion, since almost all the measured properties belong to this region [18], [37]. We computed the fitting error of both the 1-pole and the 2-pole fitted equations over our averaged dielectric data, obtaining lower errors with the 2-pole equation. We chose this option since, in addition, it has the advantage of keeping the trend of the dielectric constant curve below 2 GHz. The fitting error of both the dielectric constant and the loss factor are presented in relative terms in the last column of Table 2, averaging it along the fitted frequencies. The error committed when fitting to the 2-pole Cole-Cole equation is below 4% for every tissue.

C. UNCERTAINTY OF THE OBTAINED PROPERTIES OF BIOLOGICAL TISSUES

The repeatability and the combined uncertainty of each tissue are presented in Table 3, averaging for three different frequency regions. When measuring the saline solution for assessing the system uncertainty in Section II-C, the repeatability is affected by random errors, since this liquid is completely homogeneous. On the contrary, when measuring biological tissues, the main contribution to this type

TABLE 3. Repeatability and combined uncertainty in the measured dielectric constant and loss factor, for each tissue and frequency region.

Tissue	Repeatability						Combined uncertainty					
	0.5 – 10 GHz		10 – 18 GHz		18 – 26.5 GHz		0.5 – 10 GHz		10 – 18 GHz		18 – 26.5 GHz	
	ε_r'	ε_r''	ε_r'	ε_r''	ε_r'	ε_r''	ε_r'	ε_r''	ε_r'	ε_r''	ε_r'	ε_r''
Aorta	5.91	6.66	6.12	5.82	7.48	6.53	5.91	6.67	6.13	6.11	7.52	7.22
Bladder	2.31	1.90	2.80	1.58	3.57	1.81	2.32	1.96	2.82	2.46	3.67	3.56
Blood	4.12	4.15	4.75	5.19	5.41	5.85	4.13	4.18	4.76	5.52	5.47	6.60
Colon	4.70	5.46	7.04	9.00	7.84	12.23	4.71	5.48	7.05	9.19	7.89	12.61
Esophagus	1.95	1.97	2.57	2.87	2.73	4.55	1.97	2.03	2.60	3.43	2.85	5.49
Fallopian tubes	3.57	3.46	4.05	2.78	4.84	3.50	3.58	3.49	4.07	3.36	4.91	4.65
Fat	42.62	46.41	44.10	49.26	43.02	57.08	42.62	46.42	44.10	49.30	43.03	57.17
Gallbladder	5.31	5.93	5.52	7.20	5.90	8.87	5.31	5.96	5.54	7.45	5.96	9.39
Heart	1.64	1.56	2.25	3.53	2.46	5.69	1.66	1.64	2.28	4.00	2.60	6.46
Kidney	4.21	5.03	7.11	3.39	9.77	5.25	4.22	5.05	7.12	3.88	9.80	6.08
Liver	2.07	1.48	2.14	1.82	2.32	2.08	2.09	1.56	2.17	2.62	2.46	3.70
Lung	31.92	29.02	36.31	31.73	37.17	39.93	31.92	29.03	36.31	31.79	37.18	40.05
Muscle	2.89	2.37	4.11	4.60	4.35	6.83	2.90	2.42	4.13	4.97	4.42	7.48
Ovary	2.57	2.24	2.90	2.75	2.97	3.63	2.59	2.30	2.93	3.34	3.08	4.75
Pancreas	22.36	24.54	21.44	25.56	20.73	26.78	22.36	24.54	21.44	25.63	20.75	26.96
Skin	11.37	13.75	10.48	15.14	9.19	15.07	11.37	13.76	10.49	15.25	9.23	15.38
Small intestine	2.55	4.49	3.07	3.91	4.09	5.74	2.56	4.51	3.09	4.34	4.17	6.51
Spleen	2.97	5.18	3.22	7.97	5.09	9.21	2.99	5.20	3.24	8.19	5.16	9.71
Stomach	2.45	2.23	3.62	4.34	4.23	6.20	2.46	2.28	3.64	4.73	4.31	6.91
Uterine matrix	2.69	2.15	3.15	5.88	4.89	7.42	2.70	2.20	3.17	6.17	4.96	8.03

of uncertainty is their inhomogeneity [33]. For this reason, the repeatabilities shown in Table 3 are much higher than those of Table 1 (uncertainty source number 1). As expected, this is the main contribution to the combined uncertainty, having values of the same order of magnitude for many of the measured tissues. In general, for both the dielectric constant and the loss factor, repeatability and total uncertainty are smaller at lower frequencies and increase with it.

Fat, lung, pancreas, and skin showed huge uncertainties in comparison to the rest of characterized tissues. With the exception of pancreas, greater repeatability values were expected for the other three tissues, as they already showed large values in [7]. In case of lung tissue, the dielectric properties vary greatly depending on the breathing state, whereas in the case of skin and fat their dielectric properties vary since the content of water is not homogeneous for every position, among other possible factors. Regarding pancreas tissue, its large uncertainty may be due to a large natural inhomogeneity of this tissue, although further histological analysis should be carried out in order to properly analyze the behavior of this particular tissue and which factors cause such inhomogeneity. Besides, the repeatability is also affected by other factors to a greater or lesser extent [27], [45]. Some factors are: blood perfusion caused by measuring at *in vivo* conditions, as exposed in [11]; possible presence of air gaps between the tissue and the sensor or tissue damaging [13], [27]; and measurement pressure [13]. The pressure applied at measuring could not be studied as a common uncertainty source to all tissues since is slightly different for each of them, given their varying elasticity. Besides, we applied different forces in a single position of each tissue before characterizing them, confirming that the differences were barely significant in comparison with the combined uncertainty. Hence, it has not been studied separately and it is assumed to be included in the repeatability term.

D. COMPARISON WITH PREVIOUS STUDIES

A summary of the differences found in dielectric properties among the tissues characterized in this work and in previous studies is presented in Table 4. Differences are computed as shown in (3), in relative terms of the relevant parameter.

$$\Delta\varepsilon_r^{'}(\%) = \frac{1}{n}\sum_{f=f_1}^{f_{end}}\left(\frac{\varepsilon_{lit}^{'}(f) - \varepsilon_{cole}^{'}(f)}{\varepsilon_{cole}^{'}(f)} * 100\right) \tag{3}$$

where $\Delta\varepsilon_r'$ is the average of the differences found for the real part in relative terms, n is the number of frequencies computed of the reference work from the first f_1 to the last f_{end} common to our study, ε_{lit}' is the dielectric constant of the literature reference, and ε_{cole}' is the dielectric constant of the tissues of our study, taken them from the Cole-Cole fitted equation of each tissue presented in Section III-B. The differences in the imaginary part are computed analogously.

We used the permittivity of the tissues returned by the fitted Cole-Cole equation instead of their respective average values because, in this manner, we could compare the same frequencies with those studies that provide the dielectric properties in figures or tables. In case that the properties of the reference studies are provided by fitted equations as well, 201 evenly-spaced frequencies are compared among those common between each reference study and the present one. On the other hand, showing the differences in relative terms has the advantage of giving the same weight to the permittivities of all frequencies. However, it has the drawback

TABLE 4. Summary of the differences with respect to previous studies.

Reference	Source	Conditions	Compared Frequencies	Differences (%) ($\Delta\varepsilon_r$' | $\Delta\varepsilon_r$'')
Abdilla '13 [46]	Bovine	*Ex vivo*	0.5 GHz – 26.5 GHz	Liver (3.16 | -23.57), Muscle (-8.31 | -18.20)
Andreuccetti '97 [44]	Human	*Ex vivo*	0.5 GHz – 20 GHz	Pancreas (58.50 | 84.02)
Brady '81[1] [47]	Bovine	*In vitro*	2 GHz – 4 GHz	Aorta (-4.34 | -8.29), Kidney (-11.74 | -4.74), Liver (-15.04 | -12.91), Muscle (-18.29 | -10.34)
Burdette '80[1] [13]	Canine	*In vivo*	0.5 – 11 GHz	Kidney (-9.49 | 13.16)
		In vitro		Kidney (-18.50 | -11.39)
	Human	*In vitro*	0.5 – 8 GHz	Muscle (-15.71 | -n.a.[3])
	Rat	*In vivo*	0.5 GHz – 11 GHz	Blood (10.13 | 8.11), Fat (-16.26 | -29.03)[2], Muscle (-2.28 | n.a.[3])
Farrugia '16 [18]	Rat	*In vivo*	0.5 GHz – 26.5 GHz	Liver (2.96 | -9.71)
Fornes '16 [43]	Human	*Ex vivo*	0.5 GHz – 18 GHz	Colon (-14.70 | -9.42)
Gabriel '96 [7]	Bovine	*In vitro*	0.5 GHz – 20 GHz	Fat (-34.46 | -47.87)
	Human	*In vivo*		Skin (-0.17 | 13.35)
		In vitro		Aorta (1.88 | -14.08), Bladder (-68.76 | -73.21), Ovary (-23.31 | -7.99), Small intestine (-13.74 | 9.50), Stomach (1.72 | 3.11), Uterine matrix (7.93 | -8.86)
	Ovine			Blood (-0.77 | 15.74), Colon (-14.69 | -6.02), Gallbladder (-1.16 | -0.20), Heart (-9.75 | -4.61), Kidney (-6.09 | 2.75), Liver (-14.45 | -12.29), Lung (-32.17 | -18.58), Muscle (-3.41 | -13.69), Spleen (-5.36 | 8.76)
Guardiola '18 [48]	Human	*Ex vivo*	0.5 GHz – 20 GHz	Colon (-16.36 | -28.51)
Joines '94 [42]	Human	*Ex vivo*	0.5 GHz – 0.9 GHz	Colon (-24.04 | -32.76), Kidney (2.72 | 3.50), Liver (-7.93 | -5.67), Lung (94.91 | 71.01), Muscle (-16.88 | -30.01)
Kraszewski '82 [14]	Feline	*In vivo*	0.5 GHz – 8 GHz	Kidney (-11.74 | -18.50), Liver (-4.38 | -18.40), Muscle (-9.98 | -9.56), Spleen (-4.09 | -10.60)
	Feline	*In vitro*		Kidney (-12.30 | -21.03), Liver (-1.48 | -14.57), Muscle (-9.73 | -11.33), Spleen (-3.10 | -8.82)
	Rat	*In vivo*	0.5 – 12 GHz	Kidney (-7.01 | -12.69), Liver (-8.28 | -15.30), Muscle (-3.62 | -4.96), Spleen(-2.84 | -1.93)
Lazebnik '06 [37]	Bovine	*Ex vivo*	0.5 GHz – 20 GHz	Liver (-2.93 | -12.86)
O'Rourke '07 [19]	Human	*Ex vivo*	0.5 GHz – 20 GHz	Liver (-10.39 | -15.65)
Peyman '01 [49]	Rat	*In vitro*	0.5 GHz – 10 GHz	Kidney (-23.38 | -14.17), Liver (-10.76 | -10.26), Muscle (-19.58 | -4.67), Skin (-24.91 | -6.20), Spleen (-14.15 | -6.32)
Porter '18 [50]	Bovine	*Ex vivo*	0.5 GHz – 20 GHz	Bladder (-2.33 | -1.74)
	Porcine			Bladder (2.00 | -3.16)
Salahuddin '18 [51]	Porcine	*Ex vivo*	0.5 GHz – 20 GHz	Kidney (-3.08 | -4.50)
Schwartz '85 [11]	Frog	*In vivo*	0.5 GHz – 8 GHz	Blood (21.33 | -3.21), Heart (12.63 | 11.43), Muscle (-2.03 | 7.71)
		In vitro		Heart (5.05 | 3.21), Skin (22.65 | 41.01)
Stuchly '81 [15]	Feline	*In vivo*	0.5 GHz – 1 GHz	Kidney (-26.55 | -17.98), Liver (-13.06 | 0.84), Muscle (-6.71 | 8.95), Spleen (-13.84 | -0.91)
Stuchly '82 [16]	Rat, Feline	*In vivo*	0.5 GHz – 8 GHz	Liver (-4.54 | -22.49), Muscle (-10.42 | -16.95), Spleen (-5.73 | -14.23)
Xu '87 [41]	Canine	*In vitro*	0.5 GHz – 11 GHz	Heart (-16.73 | 7.05), Kidney (-9.27 | 8.09), Liver (-4.16 | 4.10), Muscle (-9.72 | 12.03), Skin (-7.25 | 10.65)
Yilmaz '16 [20]	Rat	*In vivo*	0.5 GHz – 6 GHz	Liver (-6.64 | -15.08)

[1] Data extracted from figures
[2] Measurements only up to 2 GHz
[3] Data could not be retrieved from figures with accuracy

of getting large values of differences, especially for the loss factor, since the absolute values are quite low in comparison with those of the dielectric constant.

The dielectric properties provided in this work are higher than those presented in almost all the collected *ex vivo* works. This outcome was expected: in many of the gathered studies in which tissues are measured in different conditions, the properties were higher when measured *in vivo* [11], [13], [14].

The differences are lower with respect to the *in vivo* studies, although in general the values of this study are slightly higher than those of most of the sources. This may be due to the fact that in many of them, although stated to be *in vivo*, were performed with freshly killed specimens. Although it makes measurements easier, it avoids blood perfusion, lowering the dielectric properties. This study agrees quite well for most of the *in vivo* properties characterized in [14], [16], [18], [20], and [41]. Differences are higher comparing with [11], although as aforementioned, it can be due to the low temperature of the measured frog tissues.

IV. DISCUSSION

There is not a consensus whether it exists a difference in the dielectric properties of *in vivo* and *ex vivo* tissues [27]. However, it seems clear that leaving a tissue exposed to air at both conditions causes surface dehydration, changing the

electromagnetic properties [13]. For instance, it was noticed that the permittivity of liver tissue was decreased around a 6% after 6 minutes of excision due to this problem [18]. In our procedure, we tried to minimize it by placing the intestines above the rest of the tissues during the laparotomy, keeping them warmed and hydrated, as suggested in [27].

The tissues of the gastrointestinal tract had almost the same dielectric properties, which is due to their resemblance in structure and water content. This fact is desirable from the point of view of physical phantom development or software simulation, as the same one could be used for emulating different tissues without the need of adding more complexity to their respective setups. Other tissues such as bladder, heart or muscle have similar dielectric properties since their water content is alike as well. In general, the properties of these tissues had lower uncertainties. Although each tissue is a particular case, generally the higher its water content, the lower its uncertainty (probably because its natural heterogeneity is lower as well).

Comparing with Gabriel's database [7], no data was found for esophagus and pancreas, whereas their heart permittivity was lower and their stomach slightly higher than ours. In general, the permittivities obtained in our measurement campaign are higher than those characterized *ex vivo* in literature, as one can observe in Table 4. If the data presented in this article is used instead of Gabriel's database in either simulation or laboratory environments with electromagnetic phantoms, the propagation characteristics of WBAN applications could vary. In general, since the dielectric constants and loss factors presented in this work are higher than the previously reported ones especially in the lower frequencies (below 15 GHz), the path loss is expected to increase whereas the velocity of propagation of the electromagnetic signals would slightly decrease. Regarding the antennas performance of WBAN devices, the differences are not sufficiently large to expect significant changes either in matching or radiation patterns, although the magnitude of these differences can vary depending on the specific design of antenna considered. All the collected properties are accessible from an authorized online source [52].

V. CONCLUSION

The dielectric properties of biological tissues can have a great impact for developing either software or physical phantoms that aid in the design of Wireless Body Area Networks (WBAN) devices or systems, especially if they are intended to work in higher frequency bands than the currently deployed ones.

In this work we provide a new collection of dielectric properties of biological tissues, focusing on the tissues of the abdominal and the thoracic regions. The main advantage of this set of properties remains in that a large amount of tissues have been measured *in vivo* for a common measurement setup: wide frequency band, the same animal species, and the same measurement conditions (i.e., surgery room and temperature). Thus, a total of 20 tissues of the thoracic and the abdominal regions of porcine subjects have been measured using the open-ended coaxial method in the 0.5 – 26.5 GHz frequency band.

Particularized analysis for heart, esophagus, stomach, and pancreas are presented in this paper since these ones have been scarcely studied *in vivo* so far. All the characterized tissues are presented along with their respective Cole-Cole fitting coefficients and uncertainty. In the particular case of pancreas, results have a large uncertainty, which may be due to its natural inhomogeneity, although a further histological analysis is required. In general, results are higher than most *ex vivo* studies, including Gabriel's database, which is the most used one by far. On the other hand, although also slightly higher, they agree quite well with other *in vivo* studies.

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MATTEO FRASSON was born in Gallarate, Italy, in 1978. He received the Specialization in general and digestive surgery in 2009, and the Ph.D. degree in medicine from the University of Valencia, in 2013. In 2006, he spent one year as a Visiting Researcher with Temple University, Philadelphia, USA. After the Residency, he moved to Valencia, Spain, where he received the Fellowship in colorectal surgery in 2010. He is currently an Assistant Professor of the Universitat Politècnica de València, also a Chief of the Research Group in digestive surgery of the Research Institute La Fe, and also a Consultant Colorectal Surgeon with Hospital Universitari i Politècnic La Fe, Valencia.

Since the beginning of his career, he has focused his research in colorectal surgery and publishing 70 full articles in international peer-reviewed journal. His current research interests include colorectal cancer, anastomotic leak, gene therapy for inflammatory bowel diseases, and the use of electromagnetic waves for cancer early detection.

Dr. Frasson is currently the Chairperson of the Young Group of the European Society of Coloproctology. He is actively involved in many Spanish scientific societies, most importantly, he is the Secretary of the Colorectal Section of the Spanish Association of Surgeon and a member of the executive committee of the Spanish Society of Coloproctology. He was a recipient of the Best Spanish Publication in Coloproctology by the Spanish Association of Coloproctology in 2012 and the Best Spanish Publication in Surgery by the Spanish Association of Surgeons in 2015 with a paper focused on anastomotic leak after colon cancer resection. He is currently a Junior Editor of the journal *Colorectal Disease* and an Editor of *Cirugía Española*.

SERGIO CASTELLÓ-PALACIOS (S'18–M'18) was born in Valencia, Spain. He received the M.Sc. degree in chemical engineering from the School of Industrial Engineering, Universitat Politècnica de València, Valencia, Spain, in 2015, where he is currently pursuing the Ph.D. degree in technologies for health and well-being.

He joined to the Mobile Communications Group, iTEAM, in 2017, where his efforts are focused on developing tissue-equivalent materials in order to test microwave technologies, mainly antennas that will be used for transmitting in wireless body area networks. His work led to the registration of a patent. Since 2014, he has been with the Centre for Biomaterials and Tissue Engineering. His research interests include dielectric characterization, polymer degradation analysis, and hydrogel synthesis with controlled swelling.

ANDREA NEVÁREZ was born in Quito, Ecuador. She received the medical Ph.D. degree from the Pontificia Universidad Católica of Ecuador, in 2003. She is currently pursuing the Ph.D. degree with the Medical Department, Universitat Politècnica de València, Spain, and also with the Hospital Universitari i Politècnic La Fe, Valencia, Spain, where she received the fellowship in gastroenterology in 2010.

In 2010, she attended for two months as an Exchange Fellow with the MD Anderson Cancer Center, Houston, TX, USA. From 2010 to 2016, he was a Digestive Endoscopist in her home country. He is an Early Stage Researcher for WiBEC ITN (Wireless In Body Environment–Marie Curie Skłodowska Actions). She has co-authored four papers published in indexed journals and also has presented oral communications in international meetings. Her research interests include the development of medical devices and computer aided diagnosis systems applied to the digestive systems.

Dr. Nevárez belongs to the Spanish Digestive Endoscopic Society and is part of the study group in capsule endoscopy and enteroscopy.

VICENTE PONS BELTRÁN was born in Alboraya, Valencia, Spain, in 1965. He received the Ph.D. degree as a medical doctor from the University Miguel Hernández, in 2001. He received the Gastroenterology Fellowship in 1994.

He is currently the Head of the Digestive Endoscopy Unit, Hospital Universitari i Politècnic La Fe, Valencia. Almost from the beginning of his professional career, he has developed his work linked to gastrointestinal endoscopy, primarily in biliopancreatic tree and small bowel endoscopy. He has conducted research projects in endoscopic capsule and on the development of an enteroscopy prototype. He has authored several international publications related to capsule endoscopy.

Dr. Pons Beltrán worked for more than ten years together with researchers from the Polytechnic University of Valencia (Energy Engineering Institute, Department of Applied Physics, Technical College Engineering Design) and has led several research projects in biomedical research (Endoworm Project). He is regularly invited as a speaker at symposiums and conferences in gastrointestinal endoscopy. At the time, he is the President of the Foundation of the National Spanish Digestive Endoscopy Society.

CONCEPCION GARCIA-PARDO received the degree in telecommunication engineering the Universidad Politécnica de Cartagena, in 2007, the M.Sc. degree in information technologies and communications in 2008, the Ph.D. degree, with European mention and qualification cum laude, from the Universidad Politécnica de Cartagena, in 2012, and the Ph.D. degree in microwaves and microtechnologies with qualification Très Honorable from the Lille 1 University. Her Ph.D. Thesis received the special prize from the Universidad Politécnica de Cartagena, in 2013.

In 2012, she joined the Institute of Telecommunications and Multimedia Applications, Universitat Politècnica de València, Spain, where she is currently a Senior Researcher. She has authored more than 40 publications of journal and conference papers related to wireless communications.

Dr. Garcia-Pardo has also participated in several national and international project related to wireless communications and wireless medical devices. Her current research interests include wireless medical devices and wireless communications for body area networks. She is also part of the management committee of COST Action CA 15104-IRACON. She regularly serves as Reviewer for the main journals related to electromagnetism and propagation.