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This issue's column includes a final report on research carried out by Asimina Kiourti with support from an AP-S Doctoral Research Award, a footnote from John Mahoney to his recent article on gain formulas, winners of AP-S Research Awards from the April 2011 round, and a technical contribution from José Pereira and Pedro Pinho on bandwidth analysis using the Smith chart.

Recent Advances in Implantable Antennas for Medical Telemetry

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Abstract

Implantable medical devices (IMDs) have recently been receiving considerable attention for medical diagnosis and treatment. Some of the most crucial scientific challenges for implantable medical devices are related to the implantable antenna, which is integrated into the implantable medical device to allow its bidirectional communication with exterior monitoring/control equipment. The aim of this paper is to provide an overview of the research efforts carried out by the authors regarding the numerical design, experimental testing, and performance evaluation of implantable antennas for medical telemetry.

Keywords: Implantable antenna; Industrial Scientific and Medical (ISM) band; in vitro; Medical Implant Communications Service (MICS) band; medical telemetry; optimization; biomedical applications of electromagnetic radiation; biomedical engineering

1. Introduction

Implantable medical devices (IMDs) are used nowadays to perform an expanding variety of diagnostic and therapeutic functions [1]. Bidirectional telemetry between the implantable medical device and exterior monitoring/control equipment is most commonly performed wirelessly, by means of an integrated implantable antenna. Patch designs are preferred for implantable antenna design, because of their flexibility in conformability and shape [2]. Communication is generally performed in the Medical Implant Communications Service (MICS) band (402.0 MHz to 405.0 MHz) [3]. Numerical and experimental investigations of implantable antennas have proven to be highly intriguing, and have attracted significant scientific interest. The aim of this paper is to present the research efforts carried out by the authors in their attempt to deal with the major challenges in implantable antenna design, including:

1. Fast design of miniature antennas with optimized resonance characteristics inside the intended human-tissue implantation scenario;

2. Prototype fabrication and experimental testing of miniature antenna structures; and

3. Evaluation of the resonance, radiation, and safety performance of implantable antennas with respect to the size and operating frequency of the antenna, as well as the anatomy and dielectric parameters of the implantation site.

2. Numerical Design

2.1 Design Methodologies

Two methodologies have been suggested for fast and optimized design of implantable antennas, as shown in Figure 1 [4, 5]. Since implantable antennas are intended for operation inside human tissue rather than in free space, their design must take into account the proper dielectric loading. Both methodologies suggest the design of an "initial antenna," which exhibits the desired resonance characteristics while in the center of a 100 mm edge-tissue-simulating cube. The "initial antenna" is obtained through manual refinement of its design parameters, until the magnitude of the reflection coefficient ($|S_{11}|$) at the desired operating frequency (f_0) satisfies

$$\left|S_{11@f_0}\right| < -20 \text{ dB}. \quad (1)$$

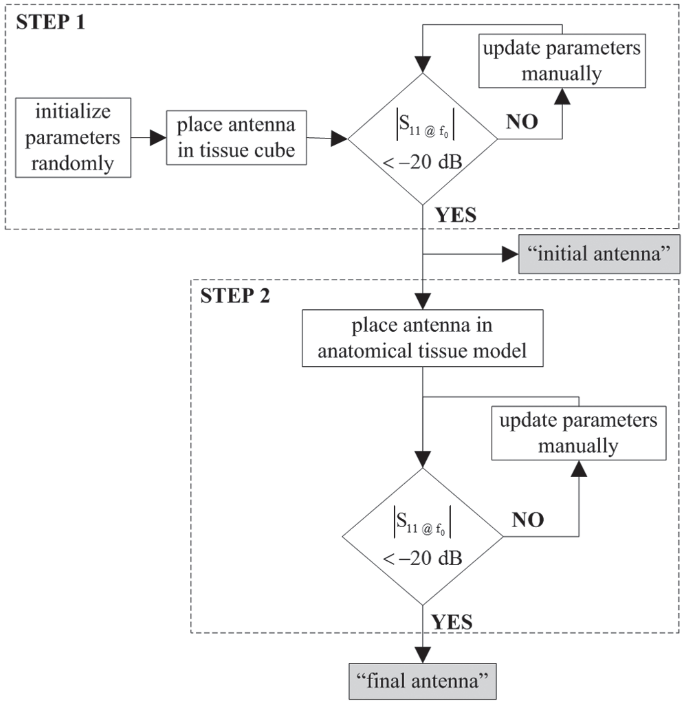

Figure 1a. A flowchart of the proposed methodology for implantable antenna design using manual refinement in the anatomical tissue model [4].

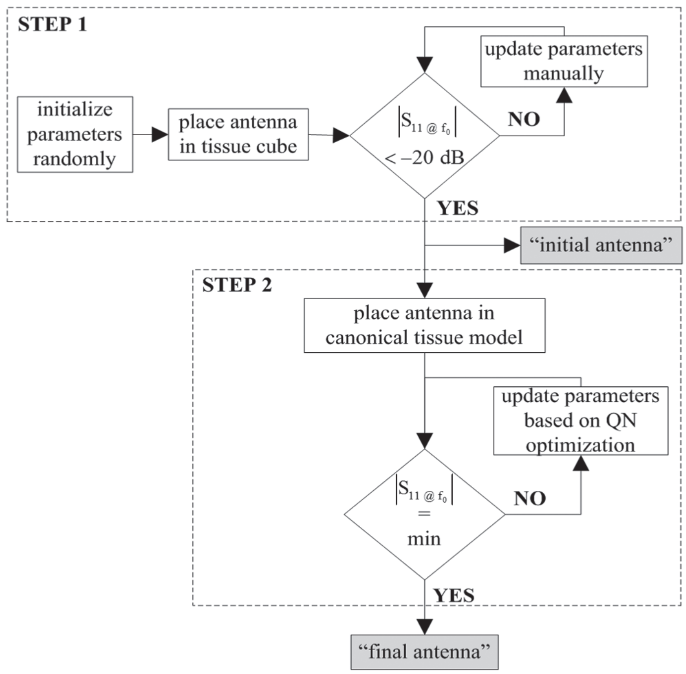

Figure 1b. A flowchart of the proposed methodology for implantable antenna design using automatic optimization in the canonical tissue model [5].

However, implanting this "initial antenna" inside the intended implantation site is expected to slightly detune its resonance frequency, attributed to the variation in dielectric loading by the surrounding tissues and exterior air. To account for this frequency detuning, the first methodology suggests implantation of the "initial antenna" inside an anatomical tissue model of the intended implantation site, and manual refinement of its design parameters (Figure 1a) [4]. In order to speed up simulations, the second methodology takes advantage of the fact that the antenna's resonance characteristics are not significantly altered within canonical or anatomical tissue models. The methodology suggests implantation of the "initial antenna" inside a canonical tissue model of the intended implantation site, and automatic quasi-Newton (QN) optimization of its design parameters (Figure 1b) [5]. Use of different numerical methods and solvers within stages of the antenna design with different requirements has been highlighted [5].

2.1 Miniature Antennas

The dimensions of the traditional half-wavelength or quarter-wavelength antennas in the frequency bands allocated for medical implants – and especially in the Medical Implant Communications Service band – make these antennas useless for implantable applications. Human tissues in which implantable antennas are intended to operate exhibit high permittivity (ε_r) values, which in turn work to advantageously reduce the physical size of the antenna. The use of patch designs for implantable antennas allows for several additional miniaturization techniques, such as the use of high-permittivity dielectric materials, the lengthening of the current-flow path on the patch's surface, the addition of a shorting pin, and patch stacking [2].

A parametric model of a miniature implantable patch antenna has been proposed that combines all of the aforementioned techniques in order to reduce size (Figure 2). The model consists of a ground plane (with a radius of R_g) and two vertically stacked patches (with radii of R_p), printed on dielectric substrates (with thicknesses of h_1 and h_2). A dielectric superstrate (with a thickness of h_3) covers the structure, to prevent contact between the metal and human tissues. Meanders of variable lengths (L_i, $i = 1,...,7;1',...,7'$) are inserted into the patches to assist in antenna miniaturization (with widths of w). A shorting pin ($S:(s_x, s_y)$) connects the ground plane to the lower patch, while a 50 ohm coaxial cable excites both patches ($F:(f_x, f_y)$). The antenna design parameters can be appropriately selected (optimized) for a good 50 ohm match at the desired operating frequency. Examples of miniature implantable antennas intended for skin implantation, and designed based on the parametric model of Figure 2, are given in Table 1 [4-7].

3. Experimental Testing

Numerical models of implantable patch antennas reported in the literature were generally simplified: zero-thickness, perfectly conducting sheets modeled the ground and patch planes; the glue used to bond the layers together was not taken into account; and ideal models of 50 ohm coaxial cables fed the structures. Another issue to be considered is that as the antenna's dimensions shrink, the tolerance to fabrication issues (e.g., soldering bumps, uncertainties in glue thickness and permittivity, etc.) becomes highly critical.

To address these limitations, an efficient design and testing methodology has been proposed, as shown in Figure 3 [8]. The basic idea is to optimize the numerical design for a specific prototype fabrication procedure and testing setup. The simplified version of the antenna model ("simplified antenna") is initially parameterized and optimized to address fabrication limitations. Antenna variables related to metallization (e.g., the thickness of the copper sheets), gluing (e.g., the permittivity and thickness of the glue layers), and feeding (e.g., the type and length of the coaxial cable) are set to the values specified by the fabrication approach under consideration. Gluing has been found to be the most critical factor. Low-permittivity glue layers isolate the high-permittivity substrate layers, thus decreasing the effective dielectric constant and electrical length of the antenna, while increasing its resonance frequency. The rest of the antenna's variables are considered as dimensions in the solution space, and are optimized based on quasi-Newton optimization. The cost function is defined as the magnitude of the reflection coefficient ($|S_{11}|$) at the desired operating frequency (f_0), i.e.,

$$\text{cost} = \left|S_{11@f_0}\right|. \tag{2}$$

Numerical sensitivity tests are subsequently performed in order to assess uncertainties that may be introduced within the in-vitro testing of the fabrication-specific antenna. The effect of minor modifications in the most sensitive antenna design and testing parameters is examined, as imposed by the fabrication approach and measurement setup under consideration. Once the prototype antenna is fabricated and tested, sensitivity tests determine the maximum allowable deviation between numerical and experimental results, and the potential need for further refinement in numerical antenna design. Deviations within the acceptable limits mean that the final prototype antenna has been obtained.

The proposed methodology has been validated within the framework of fabricating (Figure 4a) and in-vitro measuring (Figure 4b) of a miniature skin-implantable antenna for operation in the Medical Implant Communications Service band [5, 8]. Sensitivity tests related to the most-sensitive antenna design and phantom parameters indicated uncertainties of 0.5% to 6.2% in the exhibited resonance frequency. The rela-

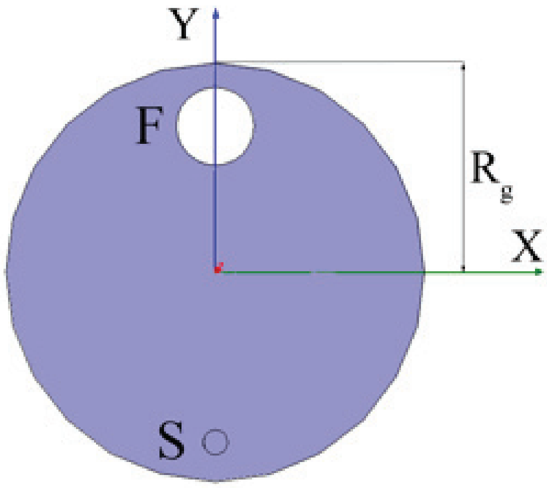

Figure 2a. The ground plane of the proposed parametric antenna model.

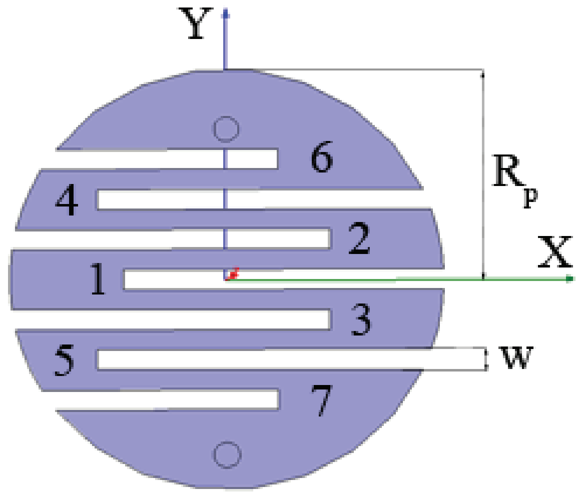

Figure 2b. The lower patch of the proposed parametric antenna model.

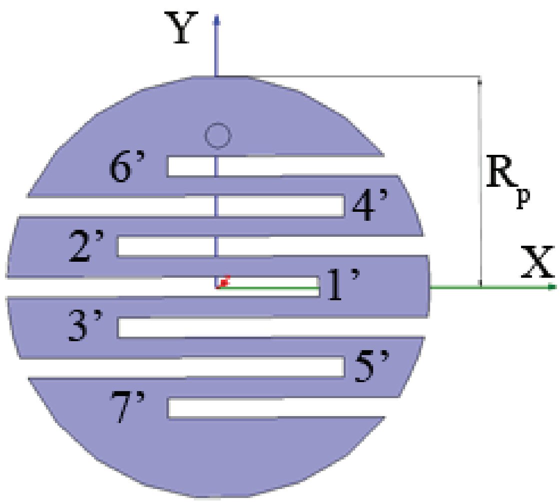

Figure 2c. The upper patch of the proposed parametric antenna model.

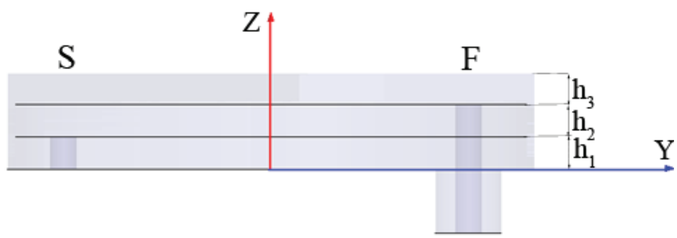

Figure 2d. A side view of the proposed parametric antenna model.

Table 1a. The parameter values of the proposed miniature skin-implantable antennas based on the parametric model of Figure 2 (in mm).

Ref.	Dielectric	R_g	R_p	(f_x, f_y)	(s_x, s_y)	h_1	h_2	h_3	w
[5]	Rogers RO 3210 (1)	6	5	(0, 4)	(1, –4)	0.6	0.6	0.6	0.4
[6]	Rogers RO 3210 (1)	4.5	4.4	(0, 3)	(0.3, –3.2)	0.6	0.6	0.6	0.5
[6]	Rogers RO 3210 (1)	4.3	4.2	(0, 3)	(0, –3)	0.6	0.6	0.6	0.35
[7]	Alumina 96% (2)	5	4.8	(0, 4)	(1.9, –4)	0.25	0.25	0.15	0.4
[4]	Alumina 96% (2)	4	3.9	(0, 3)	(3, –1)	0.25	0.25	0.15	0.5

(1) $\varepsilon_r = 10.2$, (2) $\varepsilon_r = 9.4$

Table 1b. The parameter values of the proposed miniature skin-implantable antennas based on the parametric model of Figure 2 (in mm).

Ref.	L_1	L_2	L_3	L_4	L_5	L_6	L_7	$L_{1'}$	$L_{2'}$	$L_{3'}$	$L_{4'}$	$L_{5'}$	$L_{6'}$	$L_{7'}$
[5]	6.296	8.736	8.736	2.165	2.165	–	–	9.096	8.736	8.736	7.165	7.165	6.542	–
[6]	7.193	6.536	6.536	5.237	5.237	–	–	8.299	7.936	7.936	7.337	7.337	–	–
[6]	4.896	4.767	4.767	6.217	6.217	5.933	5.933	7.896	7.767	7.767	7.017	7.017	6.133	6.133
[7]	7.696	6.833	6.733	3.349	3.349	–	–	6.796	6.733	6.433	1.050	1.050	–	–
[4]	7.392	5.827	5.827	4.485	4.485	–	–	7.392	5.827	5.827	4.485	4.485	–	–

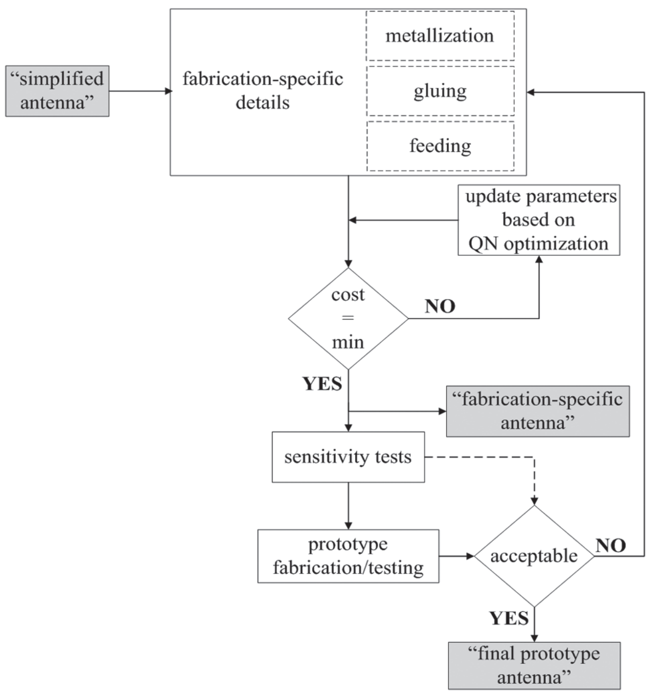

Figure 3. A flowchart of the proposed design and testing methodology for implantable antennas [8].

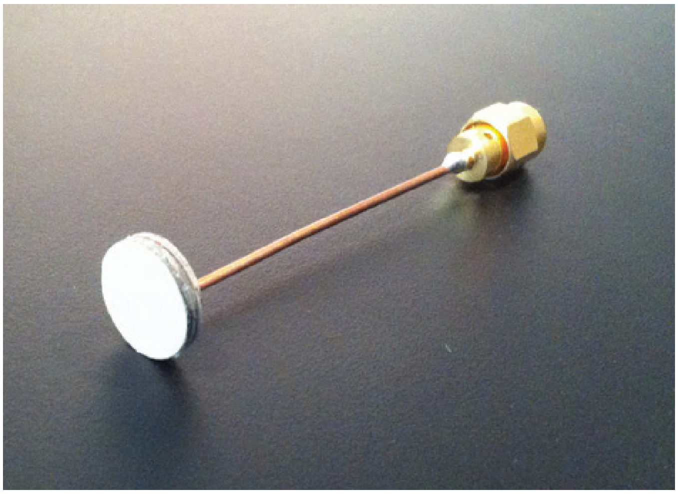

Figure 4a. Validation of the proposed design and testing methodology within the framework of fabricating a miniature skin-implantable Medical Implant Communications Service antenna [8].

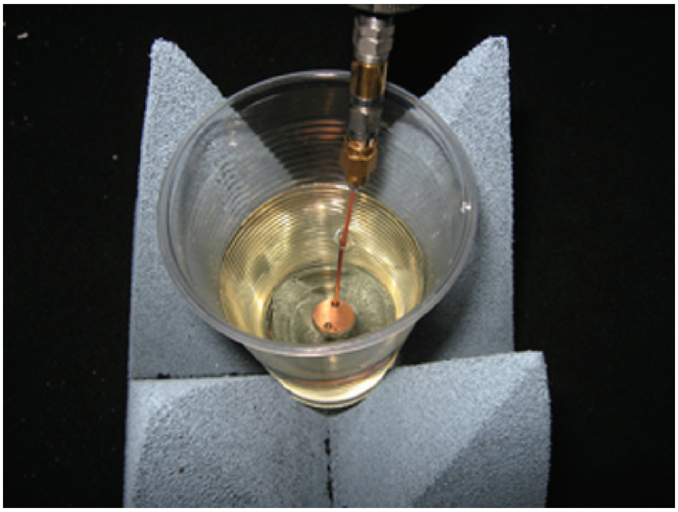

Figure 4b. Validation of the proposed design and testing methodology within the framework of testing a miniature skin-implantable Medical Implant Communications Service antenna [8].

tive antenna positioning within the phantom was shown to be of minor significance. A resonance shift of 2.5% was observed in experimental testing as compared to simulations, which was within the expected uncertainty range.

4. Performance Evaluation

4.1 Miniaturization as a Function of Gain and Safety Considerations

Implantable antenna design needs to address issues related to miniaturization, improved radiation performance, and patient safety. However, recent studies have mainly emphasized size reduction, which, in turn, degrades gain. For example, Medical Implant Communications Service implantable antennas with a volume of $3072\,\mathrm{mm}^3$ [1] and $32.7\,\mathrm{mm}^3$ [4] have been respectively found to exhibit maximum far-field gains of -23 dB and -45 dB inside a skin-tissue-simulating cube. Assessing the effect of antenna size on the induced specific absorption rate (SAR) is also important.

In order to quantify the tradeoffs among size, gain, and safety for implantable antennas, a Medical Implant Communications Service patch antenna was proposed (Figure 5a). An algorithm was applied to miniaturize it, considering single (Figure 5b) and stacked (Figure 5c) patch geometries [9]. All three PIFAs (planar inverted-F antennas) were further compared in terms of far-field gain and conformance with the IEEE restrictions for the SAR as a function of size. Generic results inside a skin-tissue-simulating cube indicated degraded gain and SAR performance with a reduction in size. Miniaturization by 32% and 65% was found to reduce the maximum far-field gain values by 5% and 19%, respectively, and the maximum allowable input powers imposed by the IEEE C95.1-1999 safety standard [10] by 21% and 44%, respectively. Antenna implantation inside a 13-tissue anatomical head model qualitatively validated the results, although quantitative deviations were observed, attributed to the difference in antenna loading by the surrounding tissues and exterior air [4, 5]. The significance of application-specific rather than miniaturization-oriented antenna design was thus emphasized.

4.2 The Effect of Operating Frequency

Various frequency bands are approved for medical implants. Although the Medical Implant Communications Service band (402.0 MHz to 405.0 MHz) is universally most commonly used, the 433.1 MHz to 434.8 MHz, 868 MHz to 868.6 MHz, and 902.8 MHz to 928.0 MHz Industrial Scientific and Medical (ISM) bands are additionally suggested for medical telemetry in some countries.

A comparative evaluation regarding the dependency of implantable antenna performance upon operating frequency and size was carried out in [5]. Patch antennas operating at 402 MHz, 433 MHz, 868 MHz, and 915 MHz were assessed for scalp implantation (e.g., intracranial pressure monitoring, brainwave sensing, stroke rehabilitation, etc). Designs exhibited identical physical dimensions (a volume of $203.6\,\mathrm{mm}^3$) but varying effective dimensions, as shown in Figure 6. Antennas at higher frequencies were found to achieve enhanced gains (a 10.7% increase in the maximum far-field gain at 915 MHz, as compared to the gain at 402 MHz); reduced SAR values (9.2% and 1.3% decreases in the 1 g and 10 g averaged SAR values); increased maximum allowable net-input-power levels (10.1% and 1.3% increases imposed by the IEEE C95.1-1999 and IEEE C95.1-2005 safety standards [10]); and more-expanded SAR distributions. The results were attributed to our choice of keeping the antennas' physical dimensions identical, and modifying their effective size. Bidirectional, half-duplex

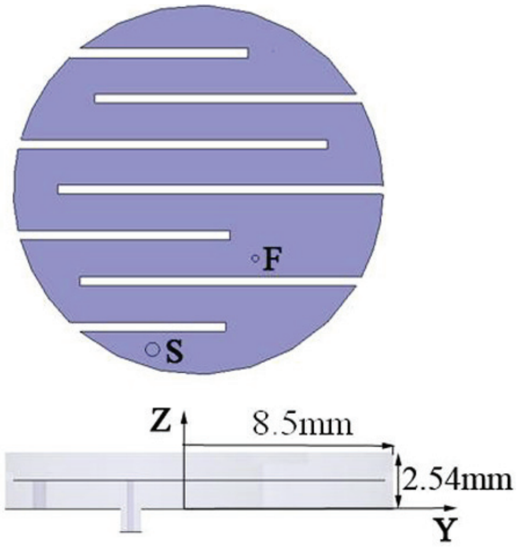

Figure 5a. The proposed 576.5 mm^3 skin-implantable Medical Implant Communications Service antenna for the assessment of miniaturization as a function of gain and safety considerations [9].

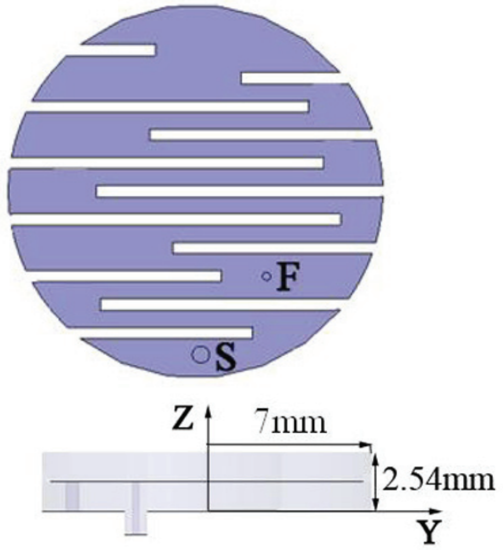

Figure 5b. The proposed 391.0 mm^3 skin-implantable Medical Implant Communications Service antenna for the assessment of miniaturization as a function of gain and safety considerations [9].

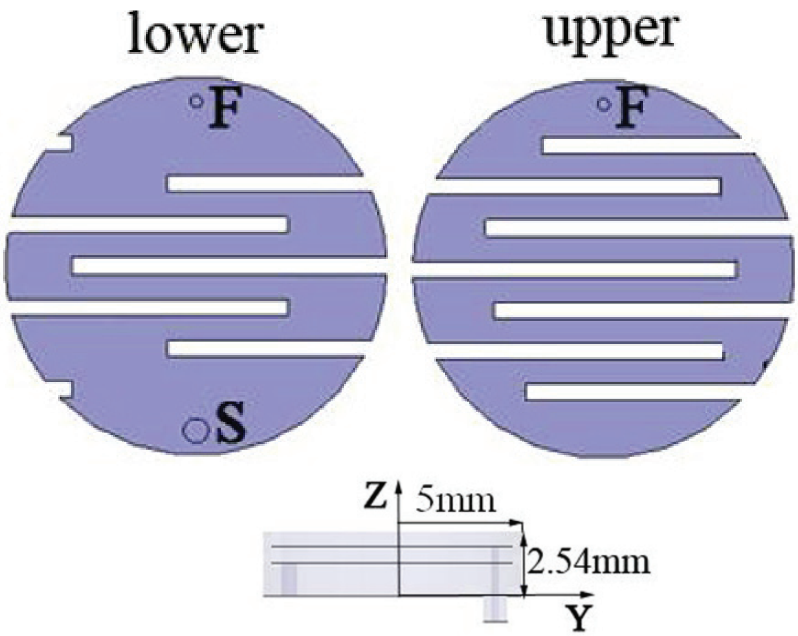

Figure 5c. The proposed 199.5 mm^3 skin-implantable Medical Implant Communications Service antenna for the assessment of miniaturization as a function of gain and safety considerations [9].

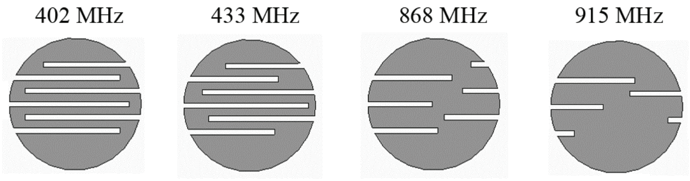

Figure 6a. The upper patches of skin-implantable antennas with identical physical dimensions for operation at 402 MHz, 433 MHz, 868 MHz, and 915 MHz [5].

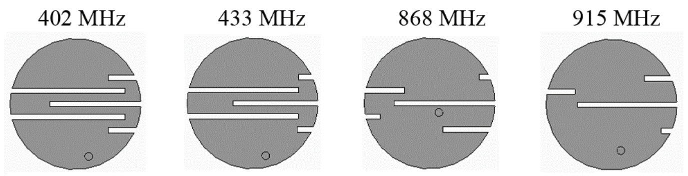

Figure 6b. The lower patches of skin-implantable antennas with identical physical dimensions for operation at 402 MHz, 433 MHz, 868 MHz, and 915 MHz [5].

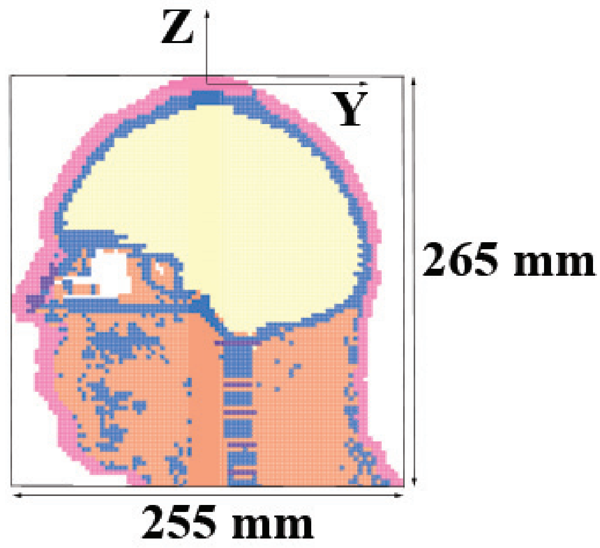

Figure 7c. The antenna implanted inside the six-tissue anatomical numerical head model [11].

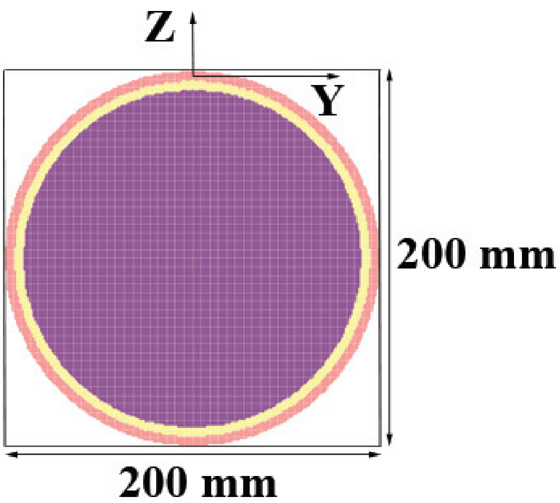

Figure 7a. The antenna implanted inside the three-layer spherical numerical head model [11].

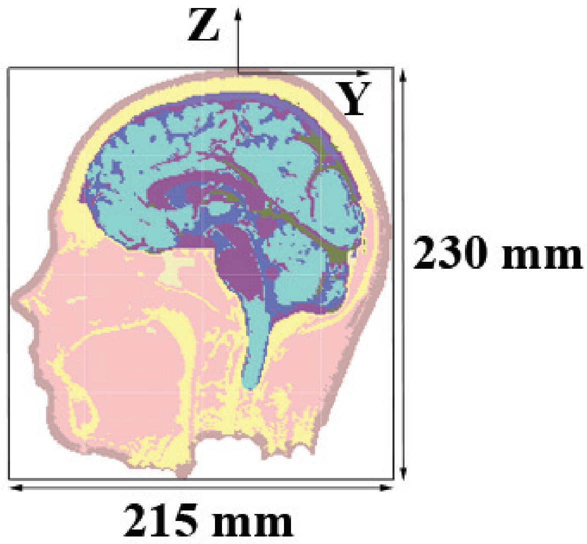

Figure 7d. The antenna implanted inside the 10-tissue anatomical numerical head model [11].

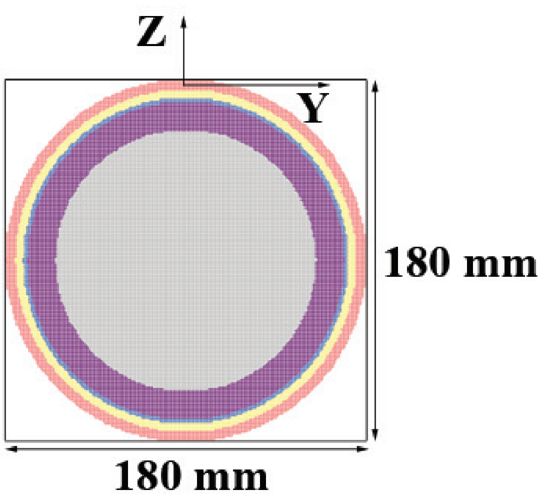

Figure 7b. The antenna implanted inside the five-layer spherical numerical head model [11].

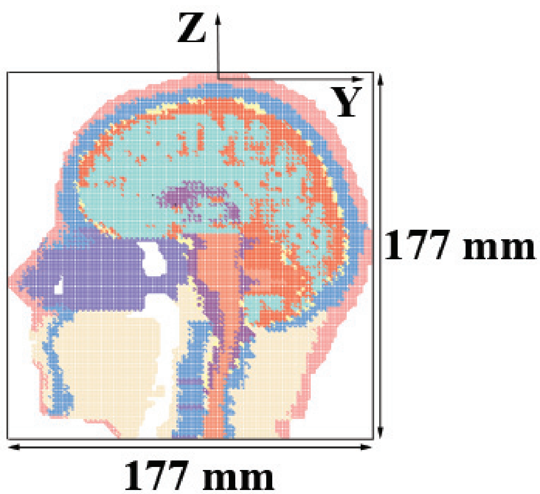

Figure 7e. The antenna implanted inside the 13-tissue anatomical numerical head model [11].

communication was further established between the implantable and exterior dipole antennas. In uplink transmission, the implanted and exterior antennas acted as the transmitting (Tx) and receiving antennas (Rx), respectively, whereas the transmitting and receiving roles interchanged for downlink transmission. Improved downlink communication was shown to occur with increasing frequency because of more-relaxed effective isotropic radiation power (EIRP) restrictions. However, a minor frequency dependence was computed for the uplink scenarios.

4.3 Effect of Tissue Model Anatomy and Dielectric Parameters

Since implantable antennas are intended for operation inside the human tissue of various individuals, it becomes crucial to assess their sensitivity to (1) the structure of the surrounding tissue environment, or, equivalently, the anatomical features of the individual; and (2) the uncertainties and intersubject variability of the tissue's dielectric parameters (permittivity, ε_r, and conductivity, σ).

A numerical study was recently carried out by the authors aiming to quantify such uncertainties [11]. The study assessed the sensitivity of a scalp-implantable Medical Implant Communications Service antenna (Figure 6a) to variations in head properties, that is, to anatomy and dielectric parameters. The resonance and radiation performance as well as safety issues were analyzed at 403.5 MHz, considering five head models (three- and five-layer spherical, six-, 10-, and 13-tissue anatomical (Figure 7) models), and seven dielectric-parameter scenarios (variations by $\pm 20\%$ in the reference permittivity and conductivity values). The anatomy of the head model around the implantation site was found to have the main effect on antenna performance, whereas overall tissue anatomy and dielectric parameters were less significant. Compared with the reference dielectric-parameter scenario within the three-layer spherical-head model (Figure 7a), maximum variations of -19.9% and $+3.7\%$ were computed for the maximum allowable net input-power levels imposed by the IEEE C95.1-1999 and IEEE C95.1-2005 safety standards [10], respectively, with maximum variations of -55.1% for the return loss and -39.2% for the maximum far-field gain. The study therefore demonstrated the need to take into account such uncertainties for implantable antenna design, compliance with safety guidelines, and evaluation of the link budget with exterior equipment. Compliance with the recent IEEE C95.1-2005 standard was found to be almost insensitive to tissue properties, as opposed to the case for IEEE Std C95.1-1999.

5. Conclusion

In this paper, an overview was presented regarding the research efforts carried out by the authors in the field of implantable antennas for medical telemetry. Efficient methodologies were initially presented for the accelerated design of implantable antennas with optimized resonance characteristics within the intended implantation scenario. A parametric model of a miniature implantable antenna was then suggested that can be appropriately refined to address any antenna (e.g., any size or material, etc.) or any tissue-model (e.g., implantation site) requirements. In order to address prototype fabrication and testing issues for implantable antennas, an iterative design and testing methodology was developed and validated. The methodology aims to determine those antenna design-parameter values that minimize deviations between numerical and experimental results. Antenna miniaturization was shown to degrade the gain and SAR performance, indicating the need for application-specific antenna design instead of solely aiming at size reduction. The selection of operating frequency was also highlighted as crucial. Implantable antennas of identical physical but varying effective dimensions were found to achieve enhanced gains and reduced SAR values with increasing frequency. Finally, taking tissue property uncertainties into account was shown to be significant for implantable antenna design and performance evaluation.

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Introducing the Authors

Asimina Kiourti received the Diploma in Electrical and Computer Engineering from the University of Patras, Greece (2008), and the MSc in Technologies for Broadband Communications from University College London, UK (2009). In October 2009, she joined the Biomedical Simulations and Imaging Laboratory, National Technical University of Athens, where she is currently working towards her PhD. She has authored or coauthored one book chapter and 14 journal and conference papers. Her current research interests include antenna theory, medical telemetry, electromagnetics and wireless communications.

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