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A Survey on Implantable Antennas for Far-field Biotelemetry Applications

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Abstract — Recently, the interest in implantable antennas has significantly increased because of their attractive and diverse medical applications. As the human body is a hostile environment for implantable antennas, where it absorbs most of the antenna's radiation, designing implantable antennas has become a challenging task. Despite the many efforts that have been made to construct successful designs of robust performance against the complicated human body environment; more efforts are still needed to overcome the current challenges. This paper aims to review recent advances in designing implantable antennas and upcoming research progress in the area of implantable antennas. To achieve this aim, the main differences in performance between antennas in free space and lossy media are emphasized firstly. Then, the main antenna's designs proposed for implantable applications are surveyed and categorized based on critical design parameters. Finally, the main characteristics of existing designs are summarized, and future needs are highlighted.

Keywords — Implantable antennas; Complementary split ring resonator; MedRadio; Split ring resonator; Far-field biotelemetry applications.

1. INTRODUCTION

Implantable devices have been recently used in a wide range of beneficial applications such as health care monitoring, capsule endoscopy and post-surgery checkups [1, 2]. In a typical healthcare system, the implantable device senses the bio signals from inside the human body and send them by the antenna to an external receiver as shown in Fig. 1 [3].

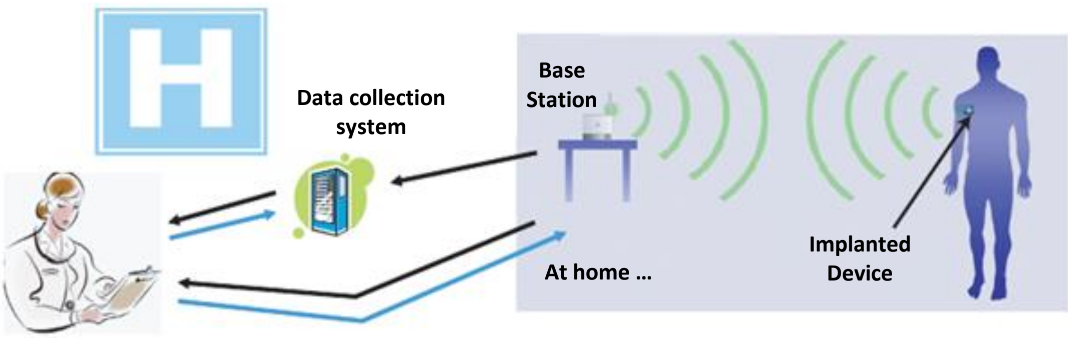

Fig. 1. A generic home health care system with a wireless implantable device [3].

The receiver can be close to the human body (near-field applications) or far at a distance longer than 3λ m (far-field applications) [4]. In both cases, the communication is mainly performed in the complicated human body.

The human body is composed of non-uniform heterogeneous and lossy tissues that absorb most of the antenna's radiations [5, 6]. It also alters most of the antenna characteristics and changes its performance as well [7]. Hence, several requirements should be considered

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and verified to guarantee a successful implantable antenna design [8]. Different techniques and investigations have been proposed in the literature to improve the performance of implantable antennas and make them robust against the human body effect. Despite these efforts, there is still a room for improvement. In this paper, the designs and investigations of implantable antennas for biomedical telemetry applications in the far-field are surveyed and summarized. In Section 2, the implantable antenna design challenges and requirements are indicated and briefly discussed. Previous works to overcome these challenges is reviewed in Section 3. The weaknesses of previous designs and future needs are discussed in Section 4. The paper is finally concluded in Section 5.

2. CHALLENGES AND REQUIREMENTS FOR THE IMPLANTABLE ANTENNA DESIGN

The human body is a very complicated environment. It is lossy, dispersive and inhomogeneous, which unavoidably affects the analysis, characterization, realization, and design of implantable antennas [9-11]. The human body is composed of different lossy tissues characterized by conductivity (σ [S/m]) and dielectric constant (ε_r). These lossy tissues absorb most of the antenna radiation, which reduces the radiated power and degrades the antenna radiation efficiency (η) [12, 13]. The relationship between the radiated power and radiation efficiency is formulated as in Eq. (1) [14]:

$$\eta = \frac{P_{rad}}{P_{in}} \tag{1}$$

where P_{rad} [W] is the radiated power and P_{in} [W] is the input power.

Unlike the case in free space, the near electric field $|\vec{E}|$ is strongly coupled with the surrounding human body tissues, which causes the power loss due to absorption as in Eq. (2) [14]:

$$P_{abs} = \frac{\omega}{2} \iiint \varepsilon_0\, \varepsilon_r''\, |E|^2\, dV \tag{2}$$

where ω [rad/s] is the angular frequency, ε_0 [F/m] is the free space permittivity, ε_r'' is the imaginary part of relative permittivity, $|E|$ [V/m] is the near electric field intensity and dV is the differential volume element over which the integration is taken.

When a fraction of the power is absorbed; the radiated power becomes smaller as [14]:

$$P_{rad} = P_{in} - P_{ref} - P_{abs} \tag{3}$$

where P_{ref} [W] is the reflected power.

The specific absorption rate (SAR [W/Kg]) is also increased when the near electric field increases as [15, 16]:

$$SAR = \frac{P_L}{\rho} = \frac{\sigma |E|^2}{2\rho} \tag{4}$$

where P_L [W/m^3] is the power loss density, ρ [kg/m^3] is the mass density and σ [S/m] is the electrical conductivity of the medium.

Unlike the gain of antennas in free space, the gain of implantable antennas in the lossy human body is directly proportional to the near magnetic field as in Eq. (5) [17, 18].

$$G_{con} = \frac{4\pi\sqrt{(\omega\mu)/(2\sigma)}\,(|H|de^{(d/\delta)})^2}{R_r\ (I_i)^2} \tag{5}$$

where μ [H/m] is the tissue permeability, $R[\Omega]$ is the intrinsic resistance, $R_r[\Omega]$ is the radiation resistance, $|H|\ [A/m]$ is the magnitude of the magnetic field intensity taken in the maximum field direction of the antenna under consideration at distance d[m], δ is the skin depth and $I_i[A]$ is the input current.

The radiation pattern and antenna bandwidth (BW) are also affected by the human body structure. The radiation pattern becomes asymmetric in the non-uniform human body but symmetric in free space [1]. Similarly, the antenna BW becomes wider in the human body than that in free space [14]. Hence, a compromise between the antenna radiation efficiency and BW should be assured, which requires accurate localization of the maximum radiation angle after implantation in the real human body.

Based on the above discussion, it can be concluded that the design of implantable antennas is very challenging and requires the satisfaction of many contradicting conditions simultaneously. These conditions include size restrictions, biocompatibility issue, specific absorption rate (SAR) for patient safety, acceptable operating BW and sufficient radiation efficiency. The detailed requirements are as follows:

a) Miniaturization: The implantable antenna must be small and can resonate at a relatively low frequency in the 401-406 MHz Medical Device Radio communications Service (MedRadio) band [19]. This requires miniaturization, which can be obtained using different techniques such as lengthening the current path of the radiator or by using high-permittivity dielectric substrate/superstrate [20].
b) Biocompatibility: The antenna should be made of biocompatible materials or enclosed by biocompatible layers to preserve patient safety as well as to protect the antenna from the conducting effect of human tissue [21, 22]. Additionally, for practical considerations, the antenna performance should be optimized considering the packaging issues [15].
c) Specific Absorption Rate (SAR) Satisfaction: The implantable antenna should comply with the SAR limitations. The SAR is required to be smaller than 1.6 W/kg when it is taken over the volume containing a mass of 1 gram of the absorbing tissue (1-g avg SAR < 1.6 W/kg) [23] or smaller than 2 W/kg for a volume containing 10 gram of the absorbing tissue (10-g avg SAR < 2 W/kg) [24].
d) Broad -10 dB BW and the coverage of the 433-434 MHz and 2.4-2.5 GHz Industrial, Scientific and Medical (ISM) band: The implantable antenna is preferred to be broad in BW. This is to guarantee good matching (S11 < -10 dB) in the real human body if detuning happens [6]. Also, it is preferred to work for other bands such as the 433-434 MHz and 2.4-2.5 GHz ISM bands, which support the functionalities of wireless power transfer and power-saving, respectively [15, 25]. Supporting such functionalities reduces the cost and pain of surgeries to replace batteries.
e) Relatively good radiation characteristics: The implantable antenna should be carefully designed with specific structures that decrease the near electric field, but increase the near magnetic field, in order to maximize the power radiated out from the human body [14].

Different designs were reported in the literature to satisfy these requirements and to overcome the challenges stated above. These designs are surveyed in the following section.

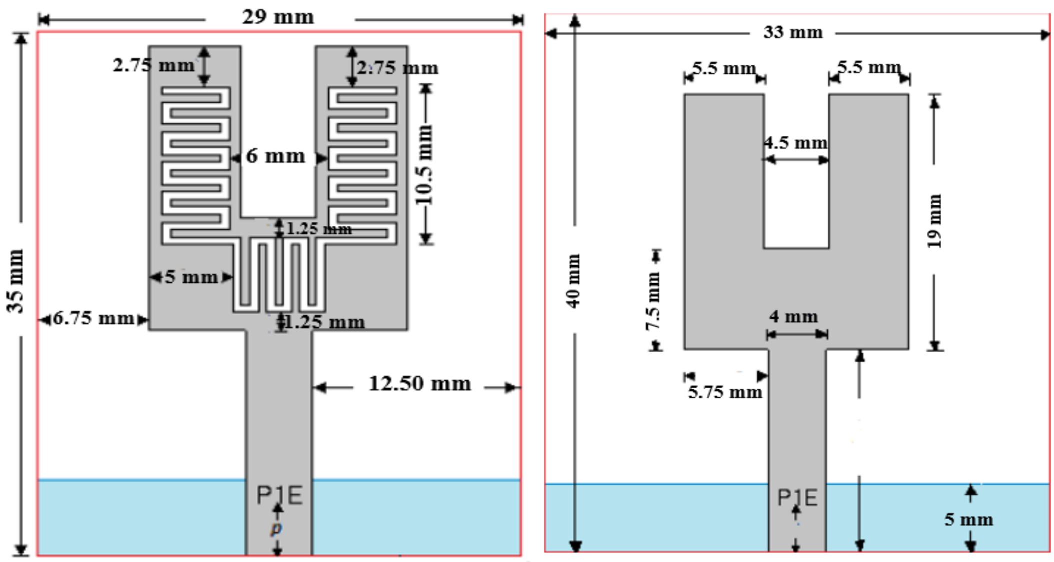
3. LITERATURE SURVEY

In this section, some of the implantable antenna designs, existing in the literature are summarized based on the techniques employed to overcome specific challenges such as employing miniaturization, gain and radiation efficiency enhancement, BW enhancement and matching stability techniques. In addition, the body models used for the evaluation and validation are summarized in this section.

3.1. Miniaturization Techniques

The implantable antenna is required to resonate at a relatively low frequency around 403 MHz for a small size, which requires miniaturization. Although the antenna works in a medium of relatively large relative permittivity, miniaturization is still needed. Different techniques were proposed in the literature to miniaturize the implantable antenna. These include: (i) lengthening the current flow-path on the radiating patch by meandering/ spiraling, (ii) stacking n number of patches, (iii) using high dielectric permittivity substrate materials, (iv) inclusion of shorting pins between the radiating patch and the ground and (v) using the metamaterial particle Split Ring Resonator (SRR) and its dual Complementary Split Ring Resonator (CSRR).

The meandering technique increases the current path over the same dimensions and size of the corresponding structures without meandering [26]. In [27], a U-shaped microstrip meandered slot antenna was proposed for remote health monitoring at 2.45 GHz. The antenna has a small size of 35×29×1.6 mm^3, which was 23.1% smaller than that for the antenna without the meandered slots. The antenna structure with and without the meandered slots is shown in Fig. 2.



(a) (b)

Fig. 2. The implantable antennas proposed in [27]: a) with meandered slots; b) without the meandered slots.

Other meandered implantable antennas, which are shown in Fig. 3, can be found in [28-30],. These antennas worked at 403 MHz for the designs in [28, 29] and at 878 MHz for the design in [30]. More examples of meandered implantable antennas can be found in [31-35] for capsule endoscopy applications. These antennas were conformal to the capsule structure and worked for wider than (400-600 MHz) which is the optimum BW for capsule applications. Dual band (401-406 MHz and 2.4-2.5 GHz) meandered implantable antennas were proposed in [36, 37] for circular and cylindrical implants of around 5 mm in radius. Additional examples of rigid structure meandered antennas were proposed in [38, 39] at 401-406 MHz, and also in [40] and [41] at 2.4-2.5 GHz and 3.525-4.79 GHz, respectively. The simple meandered structure enabled conformity and has small size for all of these designs. It also obtained a broad BW especially when being combined with SRR and CSRR such as in [37].

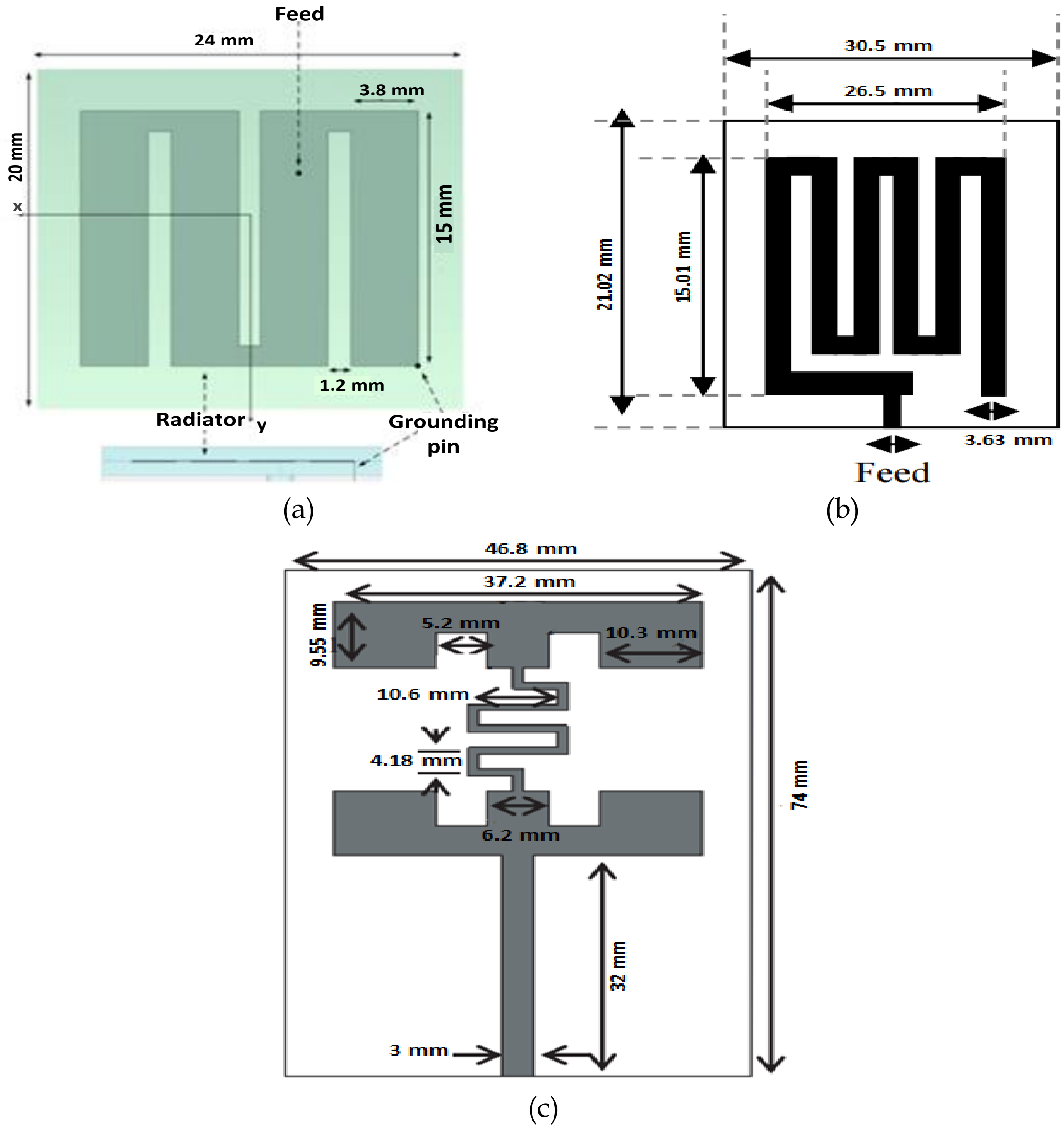


Fig. 3. The meandered implantable antennas proposed in: a) [28]; b) [29]; c) [30].

Spiraling is also one of the effective techniques used to miniaturize implantable antennas [42, 43]. Different implantable spiral structures-based designs were proposed in the literature. Examples – such as these shown in Fig. 4 - can be found in [44-46]. These antennas had a small size of 6×5×0.3 mm^3, 20×10×1.653 mm^3 and 30×30×1.6 mm^3, and resonated at 2.45 GHz, 402-405 MHz, and 2.41 GHz for the design in [44], [45] and [46], respectively. The spiral implantable antennas found in [47-56] were rigid in structure and circular in shape to conform cylindrical implants. The same BW was almost obtained for these designs in comparison with that for the meandered antennas summarized previously.

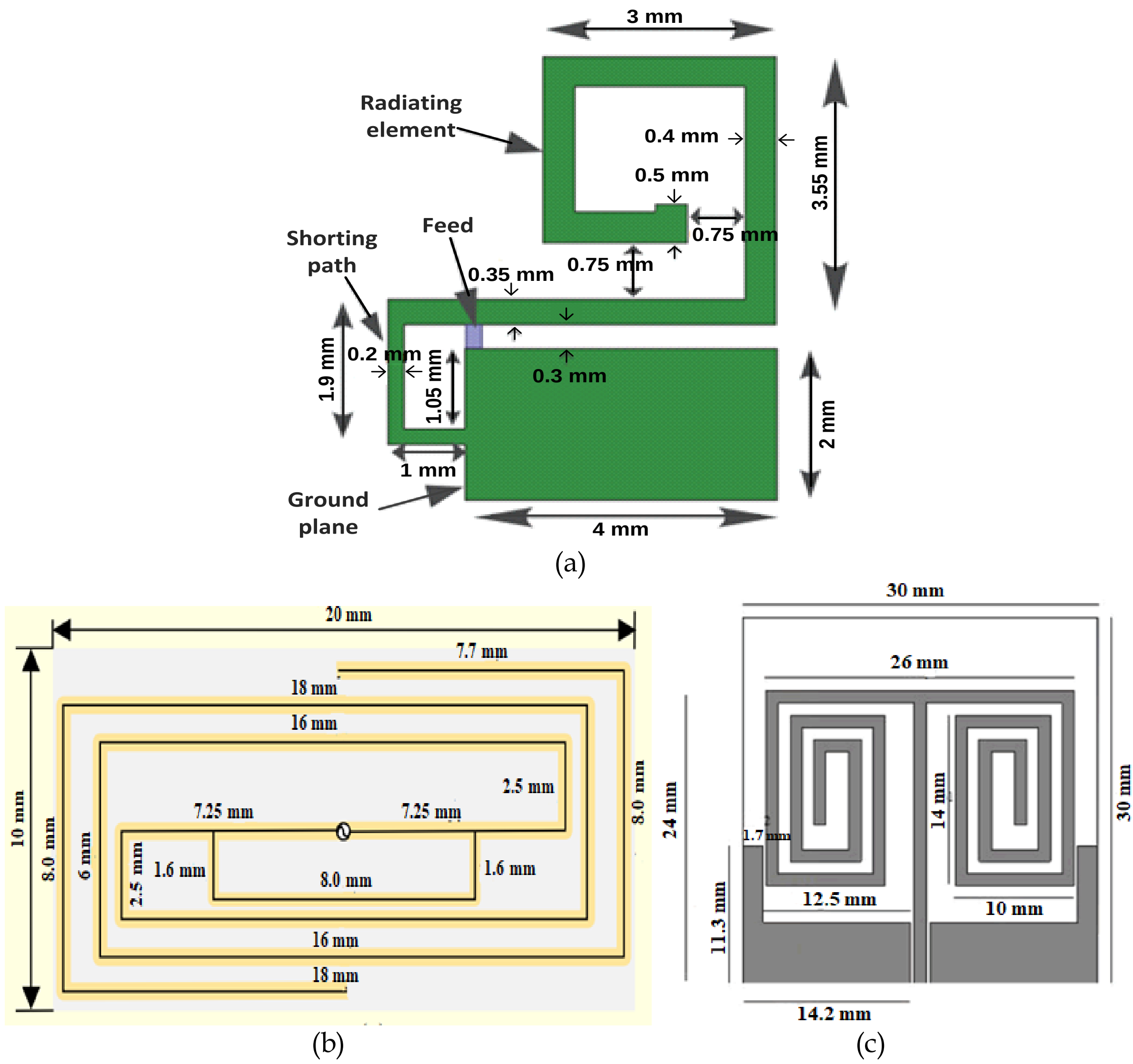
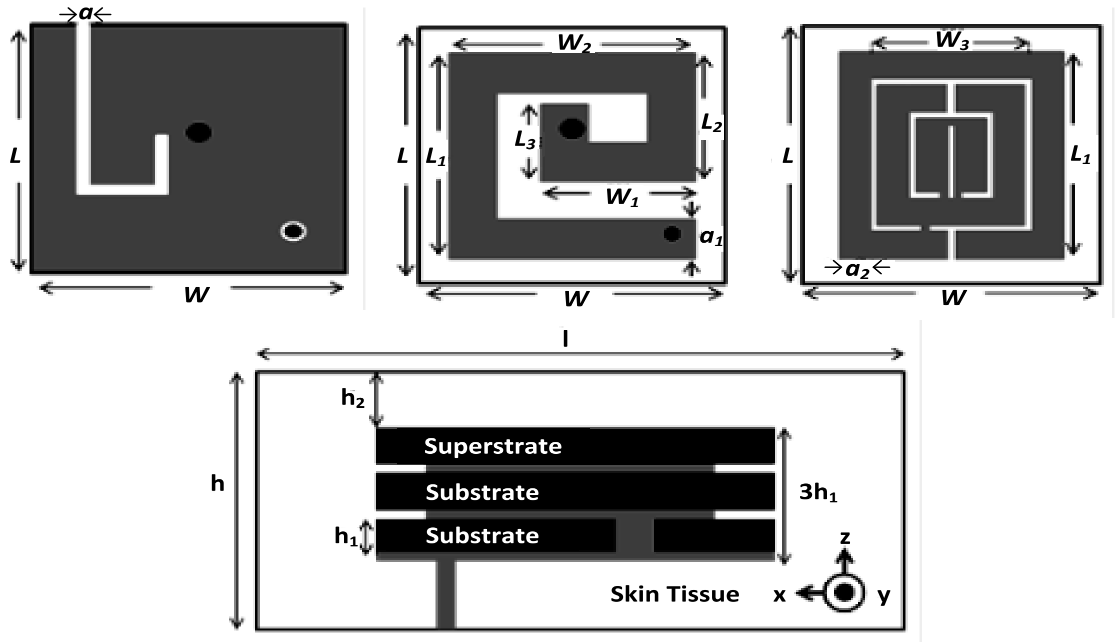
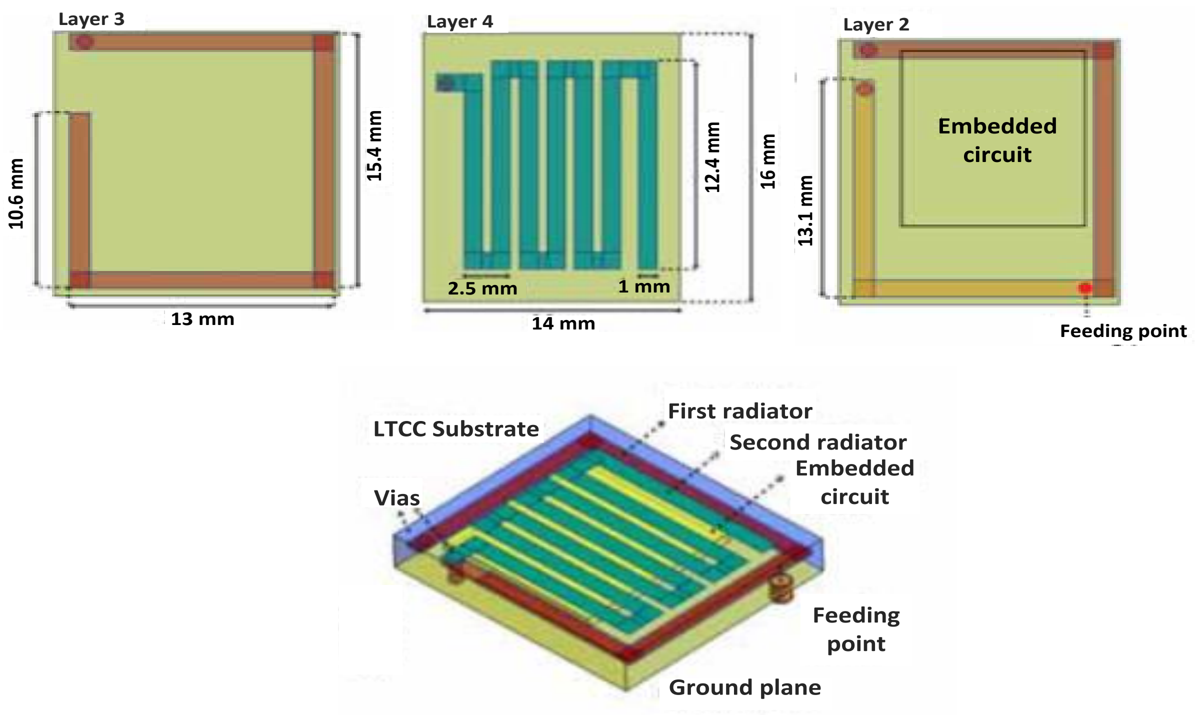


Fig. 4. The spiral implantable antennas reported in: a) [44]; b) [45]; c) [46].

As stated earlier, stacking different patch layers is also used to miniaturize the implantable antenna. Examples - shown in Fig. 5 - are found in [57, 58]. These antennas work for the 401-406 MHz MedRadio band over small sizes of 10×10×2.01 mm^3 and 14×16×2 mm^3 for the design in [57] and [58], respectively. In [57], two layers of spiral and split rings (SRs) radiating patches were used. A superstrate dielectric layer was loaded, on the top of these two layers, to prevent the direct contact with adjacent tissues. The two dielectric layers of the substrates between the patches and that of the superstrate effectively loaded the antenna and increased the effective relative permittivity, which decreased the resonant frequency [59]. The antenna in [58] was comprised of two layers of folded square inverted-F radiating patches and a top layer of a meander inverted-F patch. Again, the dielectric loading of the three substrate layers between the radiating patches increased the effective relative permittivity which shifted the resonant frequency down. Another stacked planar inverted-F antenna (PIFA) antenna of three high permittivity ($\varepsilon_r = 10.2$) layers, was proposed in [60]. Although the size of that antenna was of $\pi \times (7.5)^2 \times 1.9$ mm^3 only; it had a narrow BW of 12.4%. The antenna in [61] was composed of two radiating meandered layers and obtained a small size of 16.14×7.5×1.9 mm^3. However, it only obtained a narrow BW of 5.7%.



(a)



(b)

Fig. 5. The implantable antennas with stacked layers proposed in: a) [57]; b) [58].

Inserting a shorting pin between the ground and the radiating patch of the antenna can reduce its physical dimensions [62, 63]. The shorting and the feeding pins together form the structure of PIFA as shown in Fig. 6 [64]. The structure of the PIFA helps also obtaining other appealing features for implantable applications as will be discussed in a following section. Examples of implantable PIFA antennas can be found in [65-71].

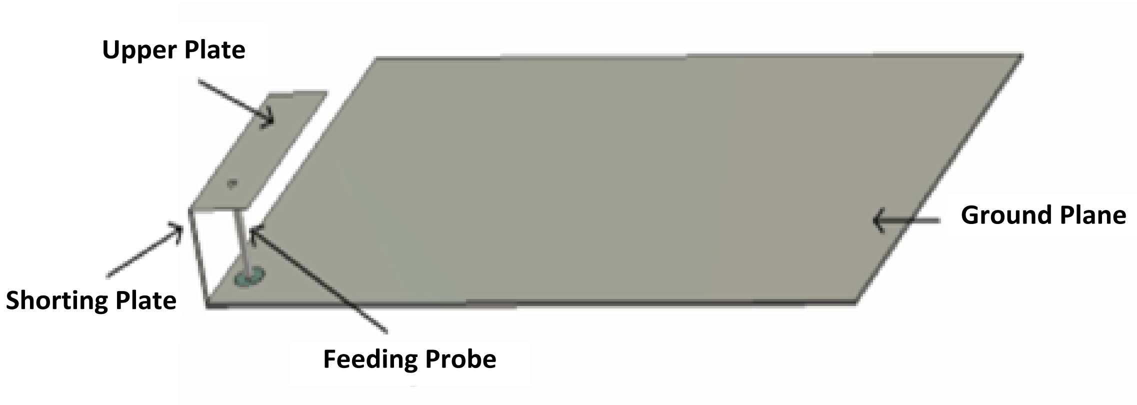


Fig. 6. Schematic diagram of a conventional PIFA antenna [64].

Another method of miniaturization is using substrates of large permittivity that reduce the physical size of the antenna [72]. Examples can be found in [73-78].

SRs and complementary split rings (CSRs) are among the most effective techniques to miniaturize antennas. They were also exploited for implantable applications [79, 80]. An example, which exploited three SRRs to obtain resonance at 403 MHz over a small size of 9.5×9.5×1.27 mm^3 can be found in [81]. The antenna's structure is shown in Fig. 7.

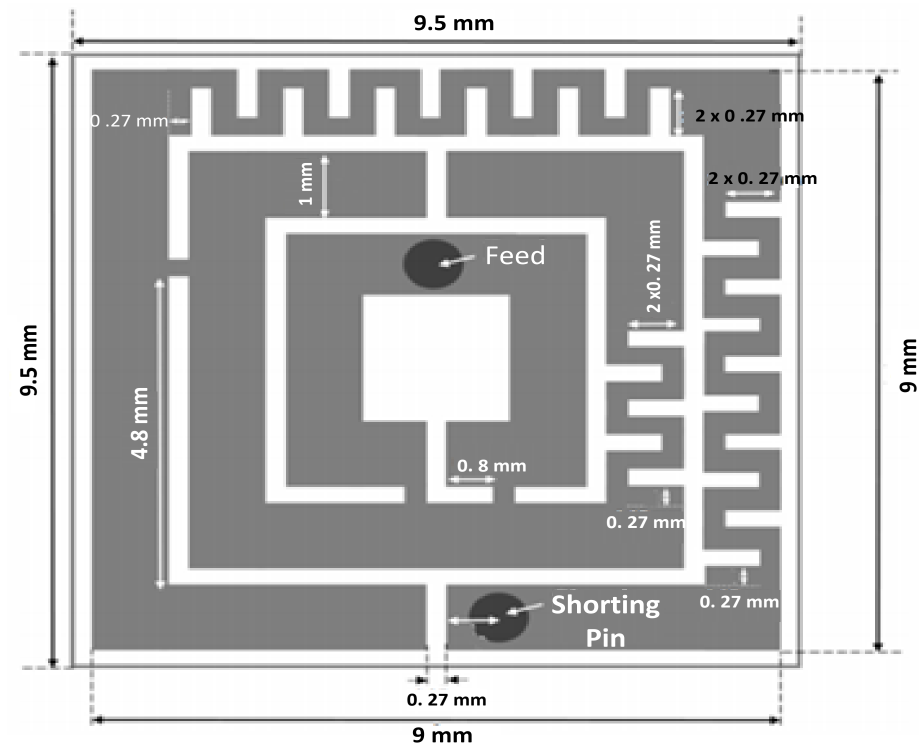


Fig. 7. The compact dual band implantable antenna, based on split-ring resonators with meander line slots configuration, reported in [81].

3.2. Gain and Radiation Efficiency Enhancement Techniques

As stated previously, implantable antennas suffer from small radiation efficiency and gain due to attenuation in the human body. Some techniques were applied in the literature to increase the radiation efficiency and gain of implantable antennas.

Insulation layers around the implantable antenna are usually used to facilitate the radiation and increase the radiation efficiency [3]. These layers decrease the near field coupling with the surrounding body tissues. This reduces the power absorption losses and thus; increases the power radiated out from the human body [14, 82]. Investigations on the effect of insulation layers on the performance of implantable antennas were provided in [83]. Different materials and thicknesses of the layers were investigated. It was found that a judicious choice of the internal biocompatible insulation leads up to a sixfold more efficient power transfer from the implanted source to the external receiver. Similar results were obtained in [84]. Other related investigations were also conducted in [82, 85-88].

Using magnetic type antennas, such as loop and slot antennas for the design, is also a very common method to improve the radiation efficiency and gain. This is because these antennas have a smaller near electric field and a larger magnetic field than the corresponding electrical type antennas [6, 17]. Some previous magnetic type antennas are summarized in Table 1. PIFA antennas have a loop in their structures between the shorting and feeding pins which increase the near magnetic field. Hence; they are more efficient than typical patch antennas. This point makes PIFAs very common for implantable applications [64, 68, 69].

Table 1. A summary of recent magnetic type antennas.

Ref	Type	Shape	Size [mm]	Frequency [MHz]	Radiation efficiency [%]	BW [MHz]	Gain [dBi]
[89]	Loop	Circular Meandered	11×0.645	402	-----	200-600	-35.6
				902	-----	800-1000	-26.3
[90]	Loop	Rectangular with CSRs	30×15	403	0.12	300-2450	-26
				433	0.2		-25.1
				868	0.3		-24
				915	0.35		-21
				2450	0.53		-15
[91]	Loop	Rectangular meandered	20×10	433	-----	327-530	-28.4
				434	-----		-----
[92]	Loop	Rectangular meandered	30×40	401	0.3	390-420	-21
				406	-----		-----
[93]	Loop	Rectangular meandered	39×12	402	0.08	334-1820	-28.4
				434	0.12		-27.1
				868	0.48		-17.6
				915	0.44		-17.8
[94]	Cavity slot	Cubic	2.8×4.0×1.6	2450	0.39	2130-2800	-22.3
[95]	Slot	Circular	10×10× 0.4	2450	2.5-5.6	-----	-9
[96]	Slot	Rectangular meandered	10×11×1.27	402-405	-----	354-469	-27.7
				433-434.8	-----		-----
[97]	Loop	Rectangular	20×44	433	0.387	-----	-20.1
[97]	Loop	Rectangular meandered	20×10.5	433	0.056	-----	-28.5

SRs and CSRs are found to increase the near magnetic field or decrease the near electric field of the implantable antenna. CSRs were integrated to a loop antenna in [90] to decrease the near electric field and, hence, increase the antenna radiation efficiency. The antenna structure is shown in Fig. 8.

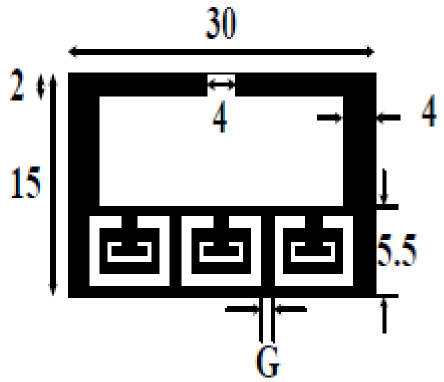


Fig. 8. The loop antenna with CSRs proposed in [90] (dimensions in mm).

A layer of multiple SRs was placed on the top of a patch antenna in [14] to increase the near magnetic field of the antenna and hence its gain. The antenna with the layer is shown in Fig. 9.

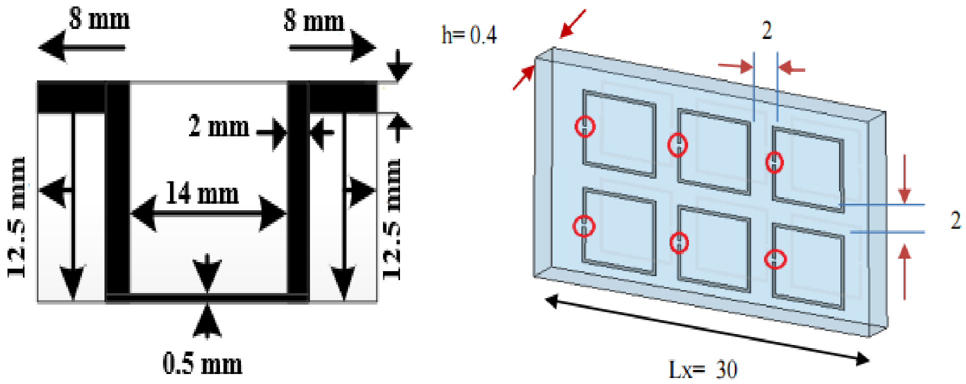


Fig. 9. The loop antenna with the SRs proposed in [14] (dimensions in mm).

3.3. Bandwidth Enhancement Techniques

Several techniques were proposed in literature to widen the BW of the implantable antennas. Traditional techniques such as combining multiple modes were proposed in [98] for a patch antenna which obtained a simulated -10 dB BW of 35% between 2.24 and 2.59 GHz. This technique was also applied in [99] in which two modes with close resonant frequencies were excited by a microstrip line with a rotated square slot in a defected ground structure.

Recently, designing the implantable antenna on a flexible structure was found to widen the implantable antenna BW. This is because the flexible structure can exploit the overall dimensions of the implantable device and, hence, a larger antenna size can be obtained. When the antenna size is increased, the BW increases accordingly. Examples can be found in [95, 100]. They are shown in Fig. 10.

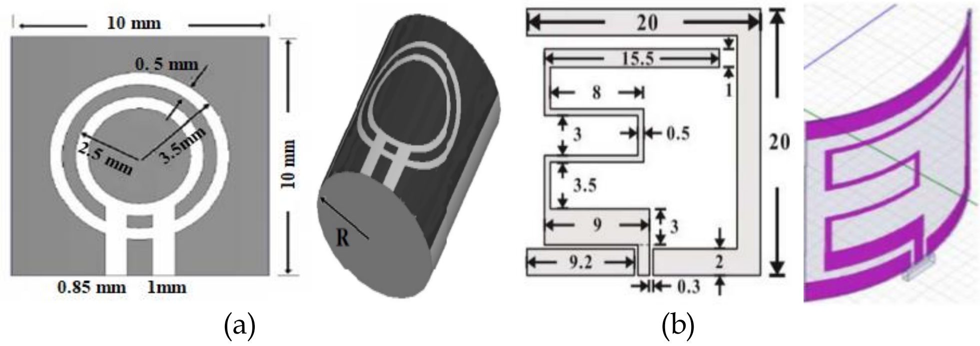


Fig. 10. The flexible implantable antennas proposed in: a) [95]; b) [100] (dimensions in mm).

3.4. Matching Stability Techniques

The antenna is considered robust when the matching level of S11 < –10 dB is maintained for different dielectric properties (ε_r, σ) of the surrounding tissues.

Antennas of a microstrip structure with a ground provide better detuning stability than that of antennas without ground (such as dipole and loop antennas), as their ground reduces the effect of adjacent tissues [101, 102]. A high permittivity superstrate along with a robust microstrip antenna design can provide sufficient decoupling from the surrounding tissues, thus keeping the antenna well-tuned.

The antenna body coupling is reduced using a high-Q narrowband microstrip antenna loaded with a high permittivity biocompatible superstrate, which result in improving the detuning immunity as proposed in [101].

In general, obtaining good matching (S11< -10 dB) over a wide range of frequency guarantees good performance, even if detuning happens in the real human body or from one tissue to another. A stable impedance matched Ultra-Wideband antenna was proposed in [103]. Another Ultra-Wideband conformal capsule antenna was also proposed in [104] to obtain a stable impedance matching.

3.5. Biocompatibility and Specific Absorption Rate

Insulation layers of biocompatible materials such as Beek are used to obtain biocompatibility. Examples of the biocompatible materials used in the literature are summarized in Table 2.

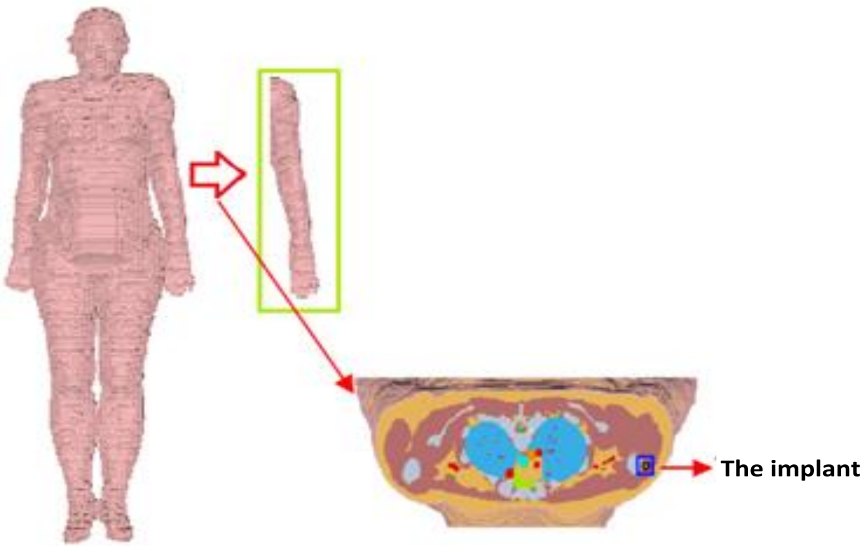
The insulation layers around the antenna decrease the near electric field coupling and the specific absorption rate accordingly [83]. The specific absorption rate can also be decreased for magnetic type antennas in comparison with electrical type antennas. These antennas have a smaller near electric field compared to the electric type antennas. Electric type antennas with magnetic layers based on SRs are found to have a smaller SAR as opposed to the same antennas without the rings [14]. CSRs are also found to decrease the near electric field and hence the SAR [90].

The performance of the implantable antenna is mainly influenced by the human body model of simulation and measurements. Thus; it is very important to validate the implantable antenna performance in different body models of different sizes and equivalent materials [14].

Table 2. Examples of materials for the biocompatible layers.

The biocompatible material	Dielectric properties		Ref
	Permittivity (ε_r)	Loss tangent (tanδ)	
Silica	3.8	0.0002	[26]
Ceramic Alumina (Al_2O_3)	9.9	0.0002	[46, 93]
Alumina	9.40	0.006	[21, 45]
Peek	3.20	0.010	[53, 83]
Teflon	2.1	0.001	[61]
Silicon	3.1	0.0025	[75]
Polypropylene	2.55	0.003	[83]
Polyethylene	2.26	0.0002	[92]
Poly dimethyl siloxane	2.8	0.005	[105]
Silastic® MDX4-4210 biomedical grade elastomer	3.0	0.001	[21,106]
Zirconia (ZrO_2)	29.0	0.001	[107]
Polyimide	3.5	0.008	[108]
Parylene-C	2.95	0.013	[109]
Ultem	3.15	0.0013	[110]

The anatomical body model is considered as the best tool for evaluating the performance of implantable antennas as it provides the best resemblance of the real human body [111]. An anatomical body model is depicted in Fig. 11.



(a) (b)

Fig. 11. An example of an anatomical body model: a) front view; b) internal cross section [6].

Other simplified with different shapes (circular, rectangular, etc.) models of uniform structures were used. The simplified models were mainly used at the initial stages of the design to accelerate the design process. In general, the resonant frequency and the -10 dB matching are almost unaffected by the shape and dimensions of the simplified body model while the radiation efficiency and gain are decreased for larger body dimensions. Thus; it is important to validate the implantable antenna performance in the anatomical body model [14]. Table 3 summarizes - the reported in literature - body models, used for simulations.

Table 3. Summary of the body models, used for simulations.

Ref	Simplified		Anatomical
[29]	Shape	Rectangular	-----
	Material	Multi-layer (muscle, fat and skin)	
	Size [mm^3]	378×378×199.52	
[45]	Shape	Rectangular	-----
	Material	Skin	
	Size [mm^3]	100×100×20	
[58]	Shape	Rectangular	-----
	Material	Muscle	
	Size [mm^3]	150×80×110	
[90]	Shape	Elliptic Cylindrical	-----
	Material	Muscle	
	Size [mm^3]	$180 \times 100 \times 50$	
[91]	Shape	Elliptic Cylindrical	CST Laura human voxel body model Age: 43 Year Weight: 51 kg Length: 163 cm
	Material	Muscle	
	Size [mm^3]	$180 \times 100 \times 50$	
[104]	Shape	Rectangular	-----
	Material	Muscle	
	Size [mm^3]	$60 \times 60 \times 70$ 100×100× 110	
[105]	Shape	Cylindrical	-----
	Material	Multi-layer (muscle, fat and skin)	
	Size [mm^3]	$\pi \times (40)^2 \times 90$	
[110]	Shape	Rectangular	CST Ella human voxel body model Age: 26 Year Weight: 57.3 kg Length: 136 cm
	Material	Multi-layer (muscle, fat and skin)	
	Size [mm^3]	100×100× 90	
[112]	Shape	Spherical	-----
	Material	Muscle	
	Size [mm^3]	$\frac{4}{3} \times \pi \times (100)^3$	
[113]	Shape	Conical	CST Katja human voxel body model Age: 43 Year Weight: 62 kg Length: 163 cm
	Material	two layers (muscle and bone)	
	Size [mm^3]	72×122× 190	

Different values of radiation efficiency and gain were obtained in the same body model for different aspect ratios [14]. Longer body models tend to underestimate the gain and radiation efficiency values.

For measurements, homogeneous liquid body phantoms or/and heterogeneous pork are mainly used. The homogeneous liquid body phantoms are usually prepared from water, salt, and sugar that are added together with specific percentages to obtain specific dielectric properties that resemble a human body tissue at a specific frequency. The preparation method can be found in [14, 15]. The liquid body phantom is exhibited in Fig. 12.

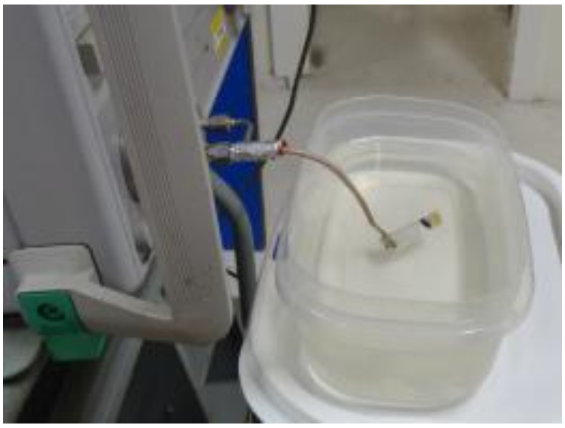
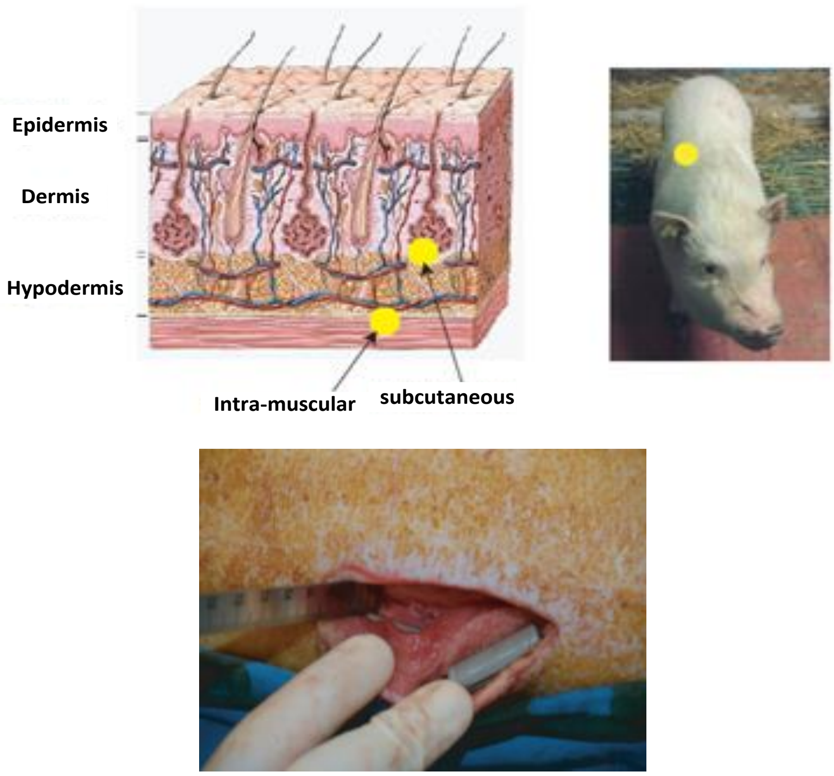


Fig. 12. Liquid body phantoms in [14].

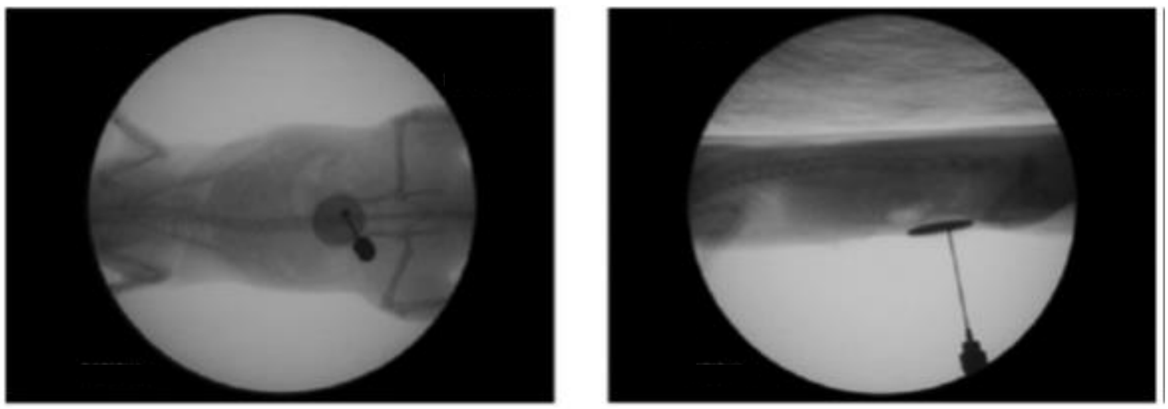
Measurements are also conducted in pork. Unlike liquid body phantoms, pork is heterogeneous and hence the antenna performance at different frequencies can be measured from pork interior. Pork phantoms are shown in Fig. 13.

Fig. 13. Pork phantoms [14].

Measurements in living animals (rats and pig) were also conducted in [15] and [114], respectively as shown in Fig. 14. The in-vivo testing is important to validate the antenna performance in realistic multi–tissue environments in which the dielectric properties vary with frequency, age, sex, size, and temperature. In general, the dielectric properties of pigs are very close to those of the human body and thus pigs can be considered much more accurate for the in-vivo measurements than rats.



(a)



(b)

Fig. 14. Images indicating the antenna implantation site inside**:** a) porcine [15]; b) rats [114].

4. LIMITATIONS OF THE EXISTING DESIGNS AND FUTURE NEEDS

In this section, the main limitations of the previous designs, discussed in the preceding section, are summarized as following:

- For the miniaturization techniques: most of the existing miniaturization techniques are based on meandering and spiraling. In general, spiral structures are more efficient in the human body than meandered structures [115]. However, they cannot be easily applied to some antenna structures such as loop antennas. The meandering techniques tend to narrow the antenna BW, which does not guarantee performance at the intended band of operation if detuning happens in the real human body. Using a substrate of high dielectric constant also tends to narrow the antenna BW. Although stacking multiple layers is an effective way of miniaturizing the antenna, it makes the antenna

BW narrow in general [60, 61]. Using SRs seems to be an effective miniaturization technique as these rings have many advantages for the implantable antenna in general. However, they increase the complexity of the structure and measurements [90]. Hence, new antennas based on SRs or CSRs of simple structures will be an effective way of miniaturization.

- For the gain and radiation efficiency enhancement techniques: As discussed above, insulation layers is an effective technique of reducing the near field coupling and the power loss due to absorption. However, they increase the overall thicknesses of the implantable device. Their effect is small for small thicknesses. Most magnetic antennas exploited for implantable applications are loop or slot. PIFA is also popular as it has a relatively large near magnetic field despite not being magnetic in type. In comparison with the loop antenna, PIFA provides enormous conformity to some implant structures exploiting the battery as a ground, its BW is relatively narrow [15]. Moreover, it cannot be easily designed on flexible substrates. Integrating SRs or CSRs to typical patch antennas in some manner to increase their near magnetic field will help in increasing the patch antenna efficiency and obtaining a wide BW at the same time [90].
- For the BW enhancement techniques: Although it is not always possible, especially for antennas of simple structure, widening the BW by exciting multiple resonant frequencies close to each other is very effective. Flexible antennas tend to increase the antenna BW as they exploit larger dimensions of the implant structure. However, new BW enhancement techniques are still needed for rigid antennas.
- For the matching stability techniques: Although the matching of antennas with grounds are much more stable than that without grounds, antennas without a ground such as the loop have many preferable features for implantable applications. Despite the fact that the antenna matching becomes more stable when a substrate of high dielectric constant is used, the BW tends to narrow.

In general, new designs of antennas based on SRs or CSRs with their many interesting features in terms of miniaturization, BW and radiation characteristics are still needed and highly recommended.

5. CONCLUSIONS

Implantable antennas have many attractive applications such as glucose monitoring and post-surgery checkups and, thus, have gained a wide interest. The design of implantable antennas is very challenging as they work inside the complicated human body that absorbs most of the antenna's radiation and alters its performance. Different requirements such as miniaturization, biocompatibility, stable matching and relatively good radiation efficiency and gain are needed for an efficient implantable antenna's design. This paper has surveyed the different designs reporteded in literature for implantable antennas and has summarized the design challenges and the main techniques to overcome them.

The existing miniaturization techniques are based mainly on lengthening the current path that results in narrowing the antenna BW. Other techniques, such as using high dielectric constant substrate and layers stacking, have also the effect of narrowing the antenna's BW. The options of using magnetic antennas or insulation layers could increase the radiation efficiency and gain of the implantable antennas. However, this is accompanied with either restricting the antenna's structure for specific antenna types or increasing its size. Exploiting SRs or CSRs is an effective way of increasing the radiation efficiency and gain. Yet, it sometimes increases the complexity of the design and measurements. Simpler designs based on the basic structures of SRs and CSRs are needed.

The stability of matching can be increased if a ground or high dielectric constant substrate is used. Nevertheless, this is accompanied by restricting the antenna's structure for patch antennas mainly, or narrowing the antenna's BW.

To sum up, SRs and CSRs have many appealing features for implantable applications. New designs exploiting them are highly recommended and encouraged for an efficient implantable antenna design that overcomes the current challenges. Multiple rings or multi-layered rings are recommended as they are expected to provide a larger increase in the radiated power compared to a single ring with a single layer. The rings structure parameters should be carefully investigated and optimized for maximum power radiation.

REFERENCES

[1] D. Ilka, *Analysis of Radio Propagation inside the Human Body for in-Body Localization Purposes,* MS thesis, University of Twente, 2014.

[2] Y. Li, L. Yang, W. Duan, X. Zhao, "An implantable antenna design for an intelligent health monitoring system considering the relative permittivity and conductivity of the human body," *IEEE Access*, vol. 7, pp. 38236-38244, 2019.

[3] M. Velur, K. Sri Kavya, "Implantable antennas for biomedical applications," *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 9, pp. 5632-5636, 2016.

[4] C. Liu, Y. Guo, H. Sun, S. Xiao, "Design and safety considerations of an implantable rectenna for far-field wireless power transfer," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 11, pp. 5798-5806, 2014.

[5] T. Paul, "Dual wide band implantable antenna for biomedical applications," *Gurukulam International Journal of Innovation in Science and Engineering*, vol. 2, no. 1, pp. 92-95, 2017.

[6] R. Alrawashdeh, F. Alharazneh, S. Alsarayreh, E. Aladaileh, "A novel flexible cloud shape loop antenna for muscle implantable devices," *Jordan Journal of Electrical Engineering,* vol. 5, no. 1, pp. 61-76, 2019.

[7] N. AbdRahman, Y. Yamada, M. Nordin, "Analysis on the effects of the human body on the performance of electro-textile antennas for wearable monitoring and tracking application," *Materials*, vol. 12, no. 10, pp. 1-17, 2019.

[8] C. Liu, Y. Guo, S. Xiao, "A review of implantable antennas for wireless biomedical devices," *Forum for Electromagnetic Research Methods and Application Technologies*, vol. 14, no. 3, pp. 1-11, 2016.

[9] X. Qing, Z. Chen, T. See, C. Goh, T. Chiam, "Characterization of RF transmission in human body," *2010 IEEE Antennas and Propagation Society International Symposium,* pp. 1-4, 2010.

[10] N. Kuster, Q. Balzano, "Energy absorption mechanism by biological bodies in the near field of dipole antennas above 300 MHz," *IEEE Transactions on Vehicular Technology*, vol. 41, no. 1, pp. 17-23, 1992.

[11] H. Lin, M. Takahashi, K. Saito, K. Ito, "Characteristics of electric field and radiation pattern on different locations of the human body for in-body wireless communication," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 10, pp. 5350-5354, 2013.

[12] M. Vallejo, J. Recas, P. Del Valle, J. Ayala, "Accurate human tissue characterization for energy-efficient wireless on-body communications," *Sensors*, vol. 13, no. 6, pp. 7546-7569, 2013.

[13] A. Khan, *Multi-antenna Systems for Wireless Capsule Endoscopy*, MS thesis, Aalto University, 2016.

[14] R. Alrawashdeh, *Implantable Antennas for Biomedical Applications*, University of Liverpool, 2015.

[15] F. Merli, *Implantable Antennas for Biomedical Applications,* Ph.D Dissertation, EPFL University, Lausanne, Switzerland, 2011.

[16] R. Kumar, L. Solanki, S. Singh, "SAR analysis of antenna implanted inside homogeneous human tissue phantom," *6th International Conference on Signal Processing and Integrated Networks*, Noida, India, pp. 755-759, 2019.

[17] H. Yi, K. Boyle, *Antennas: from Theory to Practice*, John Wiley and Sons, 2008.

[18] R. Moore, "Effects of a surrounding conducting medium on antenna analysis," *IEEE Transactions on Antennas and Propagation*, vol. 11, no. 3, pp. 216-225, 1963.

[19] Electromagnetic compatibility and Radio Spectrum Matters; Short Range Devices; Ultra Low Power Active Medical Implants and Peripheralsoperating in the frequency range 402 MHz to 405 MHz; Part 1 and Part 2, *European Telecommunications Standards Institute,* Std. EN 301 839-1/2 V1.3.1, 2007. < www.etsi.org>

[20] S. Bhattacharjee, S. Maity, S. Metya, C. Bhunia, "Performance enhancement of implantable medical antenna using differential feed technique," *Engineering Science and Technology, an International Journal*, vol. 19, no. 1, pp. 642-650, 2016.

[21] K. Psathas, A. Kiourti, K. Nikita, "Biocompatibility of implantable antennas: design and performance considerations," *The 8th European Conference on Antennas and Propagation*, pp. 1566-1570, 2014.

[22] Z. Yang, L. Zhu, S. Xiao, "An implantable circularly polarized patch antenna design for pacemaker monitoring based on quality factor analysis," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 10, pp. 5180-5192, 2018.

[23] IEEE Standards Coordinating Committee, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, IEEE Standard C95.1-1999, 1999.

[24] IEEE Standards Coordinating Committee, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, IEEE Standard C95.1-2005, 2005.

[25] F. Huang, C. Lee, C. Chang, L. Chen, T. Yo, C. Luo, "Rectenna application of miniaturized implantable antenna design for triple-band biotelemetry communication," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 7, pp. 2646-2653, 2011.

[26] M. Ali, E. Bashar, K. Hosain, "Circural planner inverted- F antenna for implantable biomedical applications," *2017 2nd International Conference on Electrical and Electronic Engineering*, Rajshahi, pp. 1-4, 2017.

[27] S. Sukhija, R. Sarin, "A U-shaped meandered slot antenna for biomedical applications," *Progress In Electromagnetics Research*, vol. 62, pp. 65-77, 2017.

[28] S. Mirrahimi, A. Keshtkar, A. Bayat "SAR reduction of the implanted meandered antenna with two novel antennas," *IACSIT International Journal of Engineering and Technology*, vol. 4, no. 5, pp. 508-511, 2012.

[29] N. Sulaiman, N. Samsuri, M. Rahim, F. Seman, M. Inam, "Compact meander line telemetry antenna for implantable pacemaker applications," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 10, no. 3, pp. 883-889, 2018.

[30] N. Ripin, A. Sulaiman, N. Rashid, M. Hussin, N. Ismail, "A miniaturized 878 MHZ slotted meander line monopole antenna," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 7, no. 1, pp. 170–177, 2017.

[31] S. Arefin, J. Redoute, M. Yuce, "Meandered conformai antenna for ISM-band ingestible capsule communication systems," *38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Orlando, Florida, pp. 3031-3034, 2016.

[32] J. Faerber, M. Desmulliez, "Conformal meander shaped antenna for biotelemetry in endoscopic capsules," *2015 Loughborough Antennas & Propagation Conference*, Loughborough, pp. 1-4, 2015.

[33] R. Alrawashdeh, Y. Huang, P. Cao, E. Lim, "A new small conformal antenna for capsule endoscopy," *7th European Conference on Antennas and Propagation*, Gothenburg, pp. 220-223, 2013.

[34] J. Faerber, G. Cummins, M. Desmulliez, "Design of conformai wideband antennas for capsule endoscopy within a body tissue environment," *46th European Microwave Conference*, London, pp. 1223-1226, 2016.

[35] J. Wang, M. Leach, E. Lim, Z. Wang, R. Pei, Y. Huang, "An implantable and conformal antenna for wireless capsule endoscopy," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 7, pp. 1153-1157, 2018.

[36] A. Kiourti1, K. Psathas, J. Costa, C. Fernandes, K. Nikita "Dual-band implantable antennas for medical telemetry: A fast design methodology and validation for intra-cranial pressure monitoring," *Progress in Electromagnetics* Research, vol. 141, pp. 161–183, 2013.

[37] S. Tirkey, N. Jha, R. Pandeeswari, S. Raghavan, "Design of flexible meandered loop antennas loaded with CSRR and SRR for implantable applications," *International Conference on Wireless Communications, Signal Processing and Networking*, Chennai, pp. 1595-1598, 2016.

[38] M. Sallam, A. Badawi, E. Soliman, "Design of an implantable miniaturized meander line antenna for biomedical telemetry," *10th European Conference on Antennas and Propagation*, Davos, pp. 1-4, 2016.

[39] N. Ferdous, N. Nainee, R. Hoque, "Design and performance of miniaturized meandered patch antenna for implantable biomedical applications," *International Conference on Electrical Engineering and Information Communication Technology*, Dhaka, pp. 1-4, 2015.

[40] T. Satitchantrakul, R. Silapunt, S. Sirivisoot, "Meander implantable antenna for biomedical wireless communication," *IEEE International Symposium on Antennas and Propagation*, Fajardo, pp. 1173-1174, 2016.

[41] S. Sultana, R. Basak, "Performance evaluation of meander line implantable antenna integrated with EBG based ground for anatomical realistic model," *Aiu Journal Of Science And Engineering*, vol. 18, no. 1, pp. 1-10, 2019.

[42] A. Saxena, C. Brajlata, S. Sharma, "Design, analysis and comparison of spiral antenna with hilbert antenna for implantable health and security purpose," *Research Gate,* 2015.

[43] I. Shah, M. Zada, H. Yoo, "Design and analysis of a compact-sized multiband spiral-shaped implantable antenna for scalp implantable and leadless pacemaker systems," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 6, pp. 4230-4234, 2019.

[44] M. Khan, E. Moradi, L. Sydänheimo, T. Björninen, Y. Rahmat-Samii, L. Ukkonen, "Miniature coplanar implantable antenna on thin and flexible platform for fully wireless intracranial pressure monitoring system," *International Journal of. Antennas and Propagation*, vol. 2017, pp. 1-9, 2017.

[45] J. Lee, D. Seo, H. Lee, "Design of implantable rectangular spiral antenna for wireless biotelemetry in MICS band," *Electronics and Telecommunications Research Institute Journal*, vol. 37, no. 2, pp. 204-211, 2015.

[46] M. Nachiappan, T. Azhagarsamy, "Design and development of dual-spiral antenna for implantable biomedical applications," *Biomedical Research*, vol. 28, no. 12, pp. 5237-5240, 2017.

[47] W. Huang, A. Kishk, "Embedded spiral microstrip implantable antenna," *International Journal of Antennas and Propagation*, vol. 2011, pp. 1-6, 2011.

[48] S. Kwak, K. Chang, Y. Yoon, "Small spiral antenna for wideband capsule endoscope system," *Electronics Letters*, vol. 42, no. 23, pp. 1328-1329, 2006.

[49] R. Khokle, K. Esselle, M. Heimlich, D. Bokor, "Design of a miniaturized bone implantable antenna for a wireless implant monitoring device," *Loughborough Antennas and Propagation Conference*, Loughborough, UK, pp. 1-2, 2017.

[50] V. Vijayalakshmi, T. Shanmuganantham, "Design of microstrip fed spiral shaped antenna for wearable systems," *International Conference on Innovations in Information, Embedded and Communication Systems*, Coimbatore, pp. 1-3, 2017.

[51] M. Ramzan, X. Fang, Q. Wang, N. Neumann, D. Plettemeier, "Miniaturized planar implanted spiral antenna inside the heart muscle at MICS band for future leadless pacemakers," *13th International Symposium on Medical Information and Communication Technology*, Oslo, Norway, pp. 1-4, 2019.

[52] E. Zincircioglu, İ. Pekdemir, R. Rzayew, E. Ilıksu, M. Dede, S. İmeci, T. Durak, "An antenna for implanted device systems," *International Applied Computational Electromagnetics Society Symposium-Italy,* Florence, pp. 1-2, 2017.

[53] J. Abadia, F. Merli, J. Zurcher, J. Mosig and A. Skrivervik, "3D-spiral small antenna design and realization for biomedical telemetry in the MICS band," *Radioengineering*, vol. 18, no.4, pp. 359-367, 2009.

[54] S. Kwak, K. Chang, Y. Yoon, "Ultra-wide band spiral shaped small antenna for the biomedical telemetry," *Asia-Pacific Microwave Conference Proceedings*, Suzhou, pp. 1-4, 2005.

[55] G. Collin, A. Chami, C. Luxey, P. Thuc, R. Staraj, "Human implanted spiral antenna for a 2.45GHz wireless temperature and pressure SAW sensor system," *IEEE Antennas and Propagation Society International Symposium*, San Diego, CA, pp. 1-4, 2008.

[56] J. Lee, D. Seo, "Compact and tissue-insensitive implantable antenna on magneto-dielectric substrate for wireless biotelemetry," *Journal of Electromagnetic Waves and Applications*, vol. 33, no. 18, pp. 2449-246, 2019.

[57] O. Gurdogan, A. Eren, S. Basaran, "Multilayered implantable antenna design for biotelemetry communication," *Turkish Journal of Electromechanics and Energy*, vol. 3, no. 1, pp. 27-30, 2018.

[58] A. Miquel, S. Curto, N. Vidal, J. Lopez-Villegas, F. Ramos, P. Prakash, "Multilayered broadband antenna for compact embedded implantable medical devices: design and characterization," *Progress in Electromagnetics Research*, vol. 159, pp. 1-13, 2017.

[59] A. Kiourti, K. Nikita, "Implantable antennas: a tutorial on design, fabrication, and in vitroin vivo testing," *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 77-91, 2014.

[60] C. Lee, T. Yo, C. Luo, C. Tu, Y. Juang, "Compact broadband stacked implantable antenna for biotelemetry with medical devices," *Electronics Letters*, vol. 43, no. 12, pp. 660-662, 2007.

[61] L. Jain, R. Singh, S. Rawat, K. Ray, "Stacked arrangement of meandered patches for biomedical applications," *International Journal of System Assurance Engineering and Managemen*t, vol. 9, no. 1, pp. 139-146, 2018.

[62] A. Bouazizi, N. Nasri, G. Zaibi, M. Samet, A. Kachouri, "A novel implantable Planar Inverted-F Antenna for biomedical applications," *IEEE 12th International Multi-Conference on Systems, Signals and Devices,* Mahdia, pp. 1-6, 2015

[63] Information Resources Management Association, *Nanotechnology: Concepts, Methodologies, Tools, and Applications*, 2014. <http://site.ebrary.com/id/10842065>

[64] D. Serhal, N. Nasser, M. Rammal, P. Vaudon, "Impact of Phone and Hand Position on SAR Distribution Using Liquid-Based PIFA Antenna," *Proceedings of the 8th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications*, Genoa, Italy, vol. 2, pp. 312-320, 2018.

[65] A. Harish, M. Hidayat, L. Nur, B. Nugroho, A. Munir, "Spiral-shaped printed planar inverted-F antenna for body wearable application," *11th International Conference on Telecommunication Systems Services and Applications*, Lombok, pp. 1-4, 2017.
[66] S. Sultana, M. Miran, S. Uddin, M. Naby, M. Haque, "Performance analysis of a modified implantable PIFA operates at MICS band for human head phantom model," *3rd International Conference on Electrical Information and Communication Technology*, Khulna, pp. 1-5, 2017.
[67] S. Sultana, R. Hasan, T. Kumar Mondal, R. Tusher, S. Zabin, "Performance analysis of body implantable PIFA at different substrate material," *4th International Conference on Advances in Electrical Engineering*, Dhaka, pp. 68-73, 2017.
[68] A. Bouazizi, G. Zaibi, M. Samet, A. Kachouri, "A Miniaturized invasive antenna study for a better performance in medical application," *32nd International Conference on Advanced Information Networking and Applications Workshops,* Krakow, pp. 98-103, 2018.
[69] H. Sajjad, W. Sethi, S. Khan, L. Jan, "Compact dual-band implantable antenna for E-health monitoring," *International Symposium on Wireless Systems and Networks*, Lahore, pp. 1-4, 2017.
[70] T. Houzen, M. Takahashi, K. Saito, K. Ito, "Implanted planar inverted F-antenna for cardiac pacemaker system," *International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials*, Chiba, pp. 346-349, 2008.
[71] A. Kiourti, M. Christopoulou, S. Koulouridis, K. Nikita, "Design of a novel miniaturized implantable PIFA for biomedical telemetry," *International Conference on Wireless Mobile Communication and Healthcare*, Berlin, Heidelberg, pp. 127-134, 2010.
[72] A. Kiourti, K. Nikita, "A review of implantable patch antennas for biomedical telemetry: challenges and solutions [wireless corner]," *IEEE Antennas and Propagation Magazine*, vol. 54, no. 3, pp. 210-228, 2012.
[73] T. Karacolak, A. Hood, E. Topsakal, "Design of a dual-band implantable antenna and development of skin mimicking gels for continuous glucose monitoring," *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 4, pp. 1001-1008, 2008.
[74] J. Kim, Y. Samii, "Implanted antennas inside a human body: simulations, designs, and characterizations," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 8, pp. 1934-1943, 2004.
[75] P. Soontornpipit, C. Furse, Y. Chung, "Design of implantable microstrip antenna for communication with medical implants," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 8, pp. 1944-1951, 2004.
[76] C. Yang, C. Tsai, S. Chen, "Implantable high-gain dental antennas for minimally invasive biomedical devices," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 5, pp. 2380-2387, 2013.
[77] A. Ahmed, T. Kalsoom, M. Rehman, N. Ramzan, S. Karim, Q. Abbasi, "Design and study of a small implantable antenna design for blood glucose monitoring," *Applied Computational Electromagnetics Society Journa*l, vol. 33, no. 10, pp. 1146–1151, 2018.
[78] J. Blauert, A. Kiourti, "Dual-band (2.4/4.8 GHz) implantable antenna for biomedical telemetry applications," *International Applied Computational Electromagnetics Society Symposium*, Denver, CO, pp. 1-2, 2018.
[79] X. Liu, Z. Wu, Y. Fan, E. Tentzeris, "A miniaturized CSRR loaded wide-beamwidth circularly polarized implantable antenna for subcutaneous real-time glucose monitoring," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 577-580, 2017.
[80] A. Eldek, F. Elhefnawi, "Split ring resonator-based miniaturized antennas," *28th National Radio Science Conference*, Cairo, pp. 1-7, 2011.

[81] Y. Yamac, S. Basaran, "A compact dual band implantable antenna based on split-ring resonators with meander line slots," *22nd International Conference on Applied Electromagnetics and Communications*, Dubrovnik, pp. 1-3, 2016.
[82] Y. El-Saboni, D. Zelenchuk, G. Conway, W. Scanlon, "Assessing the intrinsic radiation efficiency of tissue implanted UHF antennas," *IEEE Transactions on Antennas and Propagation*, pp. 1-10, 2019.
[83] F. Merli, B. Fuchs, J. Mosig, A. Skrivervik, "The effect of insulating layers on the performance of implanted antennas," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 1, pp. 21-31, 2011.
[84] Y. Zhao, R. Rennaker, C. Hutchens, T. Ibrahim, "Implanted miniaturized antenna for brain computer interface applications: analysis and design," *PloS one*, vol. 9, no 7, pp. e103945, 2014.
[85] Y. El-Saboni, G. Conway, W. Scanlon, "The importance of antenna near-field losses in intra-body uhf communication applications," *IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting*, San Diego, CA, pp. 399-400, 2017.
[86] H. Bahrami, B. Gosselin, L. Rusch, "Design of a miniaturized UWB antenna optimized for implantable neural recording systems," *10th IEEE International NEWCAS Conference*, Montreal, QC, pp. 309-312, 2012.
[87] K. Yazdandoost, "A 2.4 GHz antenna for medical implanted communications," *2009 Asia Pacific Microwave Conference*, Singapore, pp. 1775-1778, 2009.
[88] H. Bahrami, B. Gosselin, L. Rusch, "Realistic modeling of the biological channel for the design of implantable wireless UWB communication systems," *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, San Diego, CA, pp. 6015-6018, 2012.
[89] W. Lei, W. Guo, "A miniaturized implantable loop antenna at MICS and ISM bands for biomedical applications," *Proceedings of 2013 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications*, Singapore, pp. 1-3, 2013.
[90] R. Alrawashdeh, Y. Huang, M. Kod, A. Sajak, "A broadband flexible implantable loop antenna with complementary split ring resonators," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1506-1509, 2015.
[91] R. Alrawashdeh, Y. Huang, P. Cao, "Flexible meandered loop antenna for implants in MedRadio and ISM bands," *Electronics Letters*, vol. 49, no. 24, pp. 1515–1517, 2013.
[92] R. Alrawashdeh, Y. Huang, P. Cao, "A flexible loop antenna for total knee replacement implants in the med radio band," *2013 Loughborough Antennas and Propagation Conference*, Loughborough, pp. 225-228, 2013.
[93] N. Challa, S. Raghavan, "Design of broadband implantable loop antenna for human brain applications," *2016 International Conference on Emerging Trends in Engineering, Technology and Science*, pp. 1-5, 2016.
[94] W. Xia, K. Saito, M. Takahashi, K. Ito, "Performances of an implanted cavity slot antenna embedded in the human arm," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 894-899, 2009.
[95] S. Das, D. Mitra, "A compact wideband flexible implantable slot antenna design with enhanced gain," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 8, pp. 4309-4314, 2018.
[96] L. Xu, Y. Guo, W. Wu, "Miniaturised slot antenna for biomedical applications," *Electronic Letters*, vol. 49, no. 17, pp. 1060–1061, 2013.
[97] M. Kod, *Wireless Powering and Communication of Implantable Medical Devices*, University of Liverpool, 2016.
[98] Z. Yang, S. Xiao, "A wideband implantable antenna for 2.4 GHz ISM band biomedical application," *2018 International Workshop on Antenna Technology*, pp. 1-3, 2018.
[99] M. Samsuzzaman, M. Islam, J. Mandeep, N. Misran, "Printed wide-slot antenna design with bandwidth and gain enhancement on low-cost substrate," *The Scientific World Journal*, vol. 2014, pp. 1-10, 2014.

[100] C. Tsai, K. Chen, C. Yang, "Implantable wideband low-specific-absorption-rate antenna on a thin flexible substrate," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1048-1052, 2016.

[101] D. Nikolayev, M. Zhadobov, P. Karban, R. Sauleau, "Increasing the radiation efficiency and matching stability of in-body capsule antennas," *2016 10th European Conference on Antennas and Propagation*, Davos, pp. 1-5, 2016.

[102] S. Ali, V. Jeoti, T. Saeidi, W. Wen, "Design of compact microstrip patch antenna for WBAN applications at ISM 2.4 GHz," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 10, no. 1, pp. 401-408, 2018.

[103] A. Basir, H. Yoo, "A stable impedance matched ultra-wideband antenna system mitigating detuning effects for multiple bio-telemetric applications," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 5, pp. 3416-3421, 2019.

[104] Z. Bao, Y. Guo, R. Mittra, "An ultrawideband conformal capsule antenna with stable impedance matching," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 10, pp. 5086-5094, 2017.

[105] P. Loktongbam, S. Solanki, "Design and analysis of an implantable patch antenna for biomedical applications," *International Journal of Engineering Technology Science and Research*, vol. 4, no. 5, pp. 126-138, 2017.

[106] K. Psathas, A. Kiourti, K. Nikita, "Link budget analysis of a biocompatible dual-band implantable antenna for intracranial pressure monitoring," *2014 XXXIth URSI General Assembly and Scientific Symposium*, Beijing, pp. 1-4, 2014.

[107] A. Kaka, M. Toycan, "Miniaturized stacked implant antenna design at ISM band with biocompatible characteristics," *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 34, no. 4, pp. 1270-1285, 2015.

[108] L. Xu, Y. Guo, W. Wu, "Bandwidth enhancement of an implantable antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1510-1513, 2015.

[109] Z. Duan, Y. Guo, M. Je, D. Kwong, "Design and in vitro test of a differentially fed dual-band implantable antenna operating at MICS and ISM bands," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 5, pp. 2430-2439, 2014.

[110] A. Alemaryeen, S. Noghanian, "A wideband antenna for biotelemetry applications: design and transmission link evaluation," *2018 International Applied Computational Electromagnetics Society Symposium*, Denver, CO, pp. 1-2, 2018.

[111] R. Alrawashdeh, Y. Huang, Q. Xu, "Evaluation of implantable antennas in anatomical body models," *CST article,* 2014. <https://www.cst.com/solutions/article/evaluation-of-implantable-antennas-inanatomical-body-models>

[112] D. Nikolayev, "Modeling and characterization of in-body antennas," *2018 IEEE 17th International Conference on Mathematical Methods in Electromagnetic Theory*, Kiev, pp. 42-46, 2018.

[113] R. Alrawashdeh, "Path loss estimation for bone implantable applications," *Jordanian Journal of Computers and Information Technology*, vol. 04, no. 02, 2018.

[114] A. Kiourti, K. Psathas, P. Lelovas, N. Kostomitsopoulos, K. Nikita, "In vivo tests of implantable antennas in rats: antenna size and inter-subject considerations," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1396-1399, 2013.

[115] K. Jaehoon, Y. Rahmat-Samii, "Planar inverted-F antennas on implantable medical devices: meandered type versus spiral type," *Microwave and Optical Technology Letters*, vol. 48, no. 3, pp. 567-572, 2006.