Implantable Antennas for Bio-medical Applications

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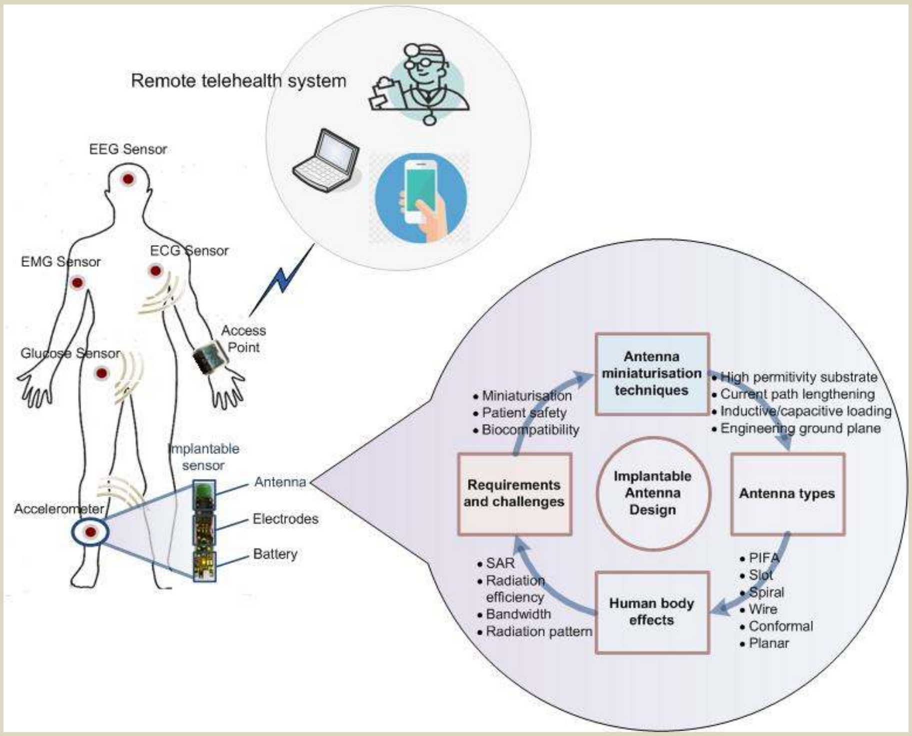

Antenna design considerations for implantable devices in remote telehealth systems

Take-Home Messages

- Implantable sensors are pivotal to telehealth systems enabling continuous monitoring of a patient's vital health signs wirelessly.
- Antennas are an integral element of these systems whose design is a complex task due to harsh and highly volatile in-body environment and requirements of robust and reliable performance while offering miniature structure, patient safety and biocompatibility.
- A comprehensive critical review on the antenna design for implantable medical devices highlighting requirements, challenges, antenna types and human body effects on their performance shows that slotted patch antennas operating at higher frequencies can serve the purpose optimally.
- The slotted patch antenna designed in the light of recommendations made offers a small size of 7.5×5×0.25 mm^3 with a -10 dB bandwidth of 25 MHz, a near-omnidirectional pattern and a gain of 1.7 dBi.
- The paper can serve as a reference for the antenna designers working in the field of implantable devices providing state-of-the-art, current advancements, requirements, challenges as well as design rules.

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***Abstract*—Biomedical telemetry has gained a lot of attention with the development in the healthcare industry. This technology has made it feasible to monitor the physiological signs of patient remotely without traditional hospital appointments and follow up routine check-ups. Implantable Medical Devices (IMDs) play an important role to monitor the patients through wireless telemetry. IMDs consist of nodes and implantable sensors in which antenna is a major component. The implantable sensors suffer a lot of limitations. Various factors need to be considered for the implantable sensors such as miniaturization, patient safety, bio-compatibility, low power consumption, lower frequency band of operation and dual-band operation to have a robust and continuous operation. The selection of the antenna is a challenging task in implantable sensor design as it dictates performance of the whole implant. In this paper a critical review on implantable antennas for biomedical applications is presented.**

***Keywords*—Implantable medical devices, Implantable sensors and antennas, Body centric wireless networks, Biomedical telemetry.**

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I. Introduction

WIRELESS communication technologies have experienced a huge development in recent years. Growth in portable and wearable wireless devices has made Body-centric applications an integral part of our daily life resulting in vastly growing field of Body-centric Wireless Networks (BCWNs). On-body, off-body and in-body communications are different forms of body centric wireless communications [1]. Wearable devices exhibit on-body communication. The communication between an on-body device and external device is referred as off-body communication. The in-body communication consists of an implantable device and an external device for health monitoring [2]. For Body-centric wireless communication networks, antennas and propagation play an important role because the antenna either work as transmitting or receiving antenna. So, if the performance of the antenna is not good it will affect the performance of whole system.

In biomedical telemetry, the IMDs are capable of monitoring patient physiological data wirelessly in real time [3], [4]. IMDs have many applications in these systems such as hyperthermia for cancer treatment, remote drug delivery and vital signs monitoring [5]–[7]. The implantable devices are placed inside the body where they monitor bio-signals (such as blood pressure and temperature signals) and send the information to the external device. They operate at either of Medical Device Radio band (MedRad) (401-406, 413-419, 426-432, 438-444, 451-457 MHz, Medical Implantable Communication Service (MICS) (402-405 MHz) or Industrial, Scientific and Medical (ISM) (2.45 GHz) band frequencies [8]. The external device can be used to process the information, transmit signal to implantable device such as wakeup signals and wireless power transfer for RF energy harvesting. It receives the information from the implantable device and send it to the monitoring unit where post processing is done to analyze the patient data by medical experts for an appropriate treatment. These health monitoring systems are very useful in diagnosing some life-threatening diseases such as cancer and diabetes in their early stages and reduce the cost and trouble of keeping the patient in hospitals significantly. A remote healthcare scenario using an implantable device is shown in Fig. 1. [8].

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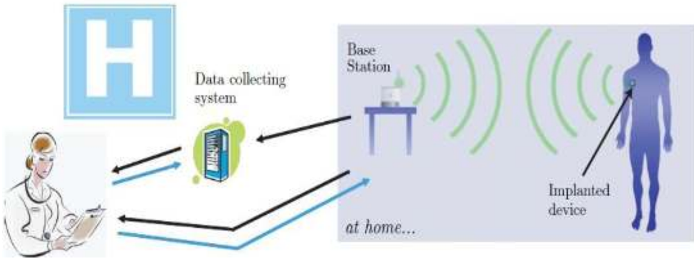


Fig. 1: Remote healthcare using implantable devices [8].

The IMDs also help in treatment and prevention of strokes and heart attacks. Blood sugar level, blood glucose level and other bio physical parameters can also be monitored using implantable medical devices. Other applications of medical implants in everyday human life for healthcare monitoring include pacemakers, defibrillators, implantable glucose sensors, pressure sensors and capsule pills, functional electrical stimulators (FES), cochlear and retinal implants, hypopnea syndrome diagnosis and chronic obstructive pulmonary disease warning etc. [8]–[16]. Implantable devices are made up of many components including antenna, battery and sensors. Reliability and robustness of the communication link between the internal and external device depends largely on the implantable antenna. The antenna is a major building block of an implantable device as the basic operational requirement of signal reception and transmission depends largely on the antenna working. Moreover, it also affects the overall size and weight of the implantable device. Furthermore, electromagnetically very harsh and lossy environment inside the human body also adds to the design complexity.

Research in this area is growing but need a good overview to make the antenna designers familiar with the state-of-the-art and recent developments. This paper attempts to provide a comprehensive review of the requirements and challenges and various techniques employed to meet them in the field of implantable antennas. Following the introduction in this section, the paper is divided in seven sections. Section II briefly highlights the use of implantable sensors in medical devices. Section III discusses various types of antennas being used in such implantable sensors and compare their performance in a critical way. Antenna design requirements and challenges based on the reviewed types are summarised in Section IV along with possible solutions. Section V details the effects of human body presence on the antenna parameters. Section VII presents the design and analyses of a miniaturized implantable antenna aimed to meet the discussed key requirements in earlier sections. Finally conclusions are made in Section VIII.

II. Implantable Sensors and Antennas

Various implantable sensors are presented in the literature. A wireless implantable device based on magnetoelectric (ME) antennas named as NanoNeuro Radio Frequency Identification (RFID) is proposed in [17] for neural recording. An array of ME antennas is used in this sensor because of their smaller size enabling miniaturization of the sensor. The ME antennas can also harvest energy which increases the sensor lifetime. A dual band antenna is designed based on impulse radio technology for wireless capsule endoscopic image transmission system in [18]. The antenna is fed by a battery powered radio transceiver. The antenna received power is used to estimate the image transmission requirement of the system. In [19], a miniaturized four element Multiple Input Multiple Output (MIMO) antenna with EBG for implantable medical devices is proposed. The antenna is tested in pork slab and operates in the ISM band with dimensions of 18.5×18.5×1.27 mm^3 and a peak gain of -15 dBi. Utilization of implantable antenna for oral cancer detection is presented in [20] employing a Planar Inverted F Antenna (PIFA). The CST voxel model Katja is used to design the human mouth. Resonant frequency showed a considerable shift when a malignant tissue is detected. An implantable RFID sensor tag for continuous glucose monitoring is discussed in [21]. This sensor system is powered by an inductive link and consists of multiple units including RFID tag, ferrite antenna, glucose sensor, potentiostat, Analog-to-Digital converter (ADC), temperature sensor and a digital baseband for signal processing. The glucose sensor has a range of 0-30 mm. It is evident that implantable antennas play a pivotal role in these applications as implantable sensors have a large dependency on the antennas.

III. Types of implantable antennas

There are different types of implantable antennas depending on the application. Key types are discussed in this section.

A. Planar Antennas

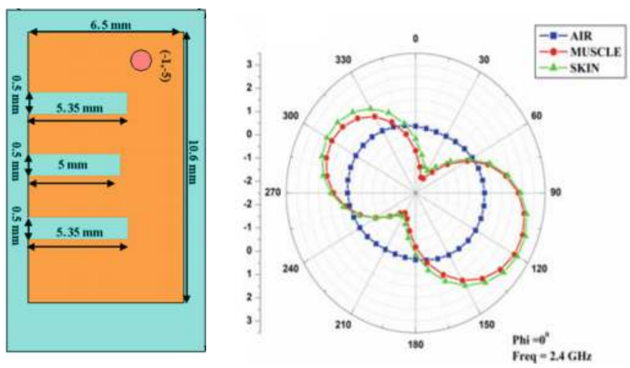
A probe-fed wideband implantable antenna with dimensions of 12×7.5×0.25 mm^3 using Rogers 6010 LM (with ϵ_r=10.2) substrate is proposed in [22]. The antenna operates in five frequency bands of 403-405 MHz, 433.1-434.8 MHz, 868-868.6 MHz, 902.8-928.0 MHz and 2.4-2.48 GHz as shown in Fig. 2 [22]. It exhibits a radiation efficiency of 80% with a bandwidth of 168.85% whereas the gain of the antenna is not reported. A flexible antenna using Poly-dimethyl Siloxane (PMDS) with ϵ_r=2.8 as base material is proposed by Fu et al. [23]. The overall dimensions of the antenna are 11×11×2 mm^3. The antenna center frequency is 2.42 GHz with realized gain of -20.8 dBi. It has a bandwidth of 10.4% while the efficiency is not reported. The antenna measurements were taken using single layer tissue model having dimensions of 150×150×90 mm^3 with ϵ_r= 37.88 and σ=1.44 S/m at 2.42 GHz.

Shah et al. have proposed a meandered line implantable antenna for intracranial pressure monitoring at 915 MHz and 2.45 GHz [24]. The antenna has a volume of 8×6×0.5 mm^3 and uses Rogers 6010 as the substrate. For biocompatibility, it is encapsulated in ceramic alumina. Human skin tissue model with dimensions of 200×200×200 mm^3 is used to test the performance. The antenna has a gain and bandwidth of -28.5 dBi and 9.84% at 915MHz and -22.8 dBi and 8.57% at 2.45 GHz while efficiency is not reported. A meander line antenna for pacemaker application operating at 402.5 MHz with a bandwidth of 33.5% is proposed by Samsuri et al. in [25]. The antenna is designed on FR-4 substrate with ϵ_r=4.7 and tan δ=0.025 having a size of 30.5×21.02×6.4 mm^3. The antenna structure and surface current density is shown in Fig. 3 [25].

Maity et al. have proposed a microstrip patch antenna with fractal geometry in [26]. The antenna has a volume of 11.44×11.44×0.275 mm^3 and Silicon with ϵ_r=11.7 is used as the substrate. Gain and efficiency of the antenna are not reported while the bandwidth is 1.5%. The geometry and radiation pattern of the antenna are shown in Fig. 4 [26].

B. Wire Antennas

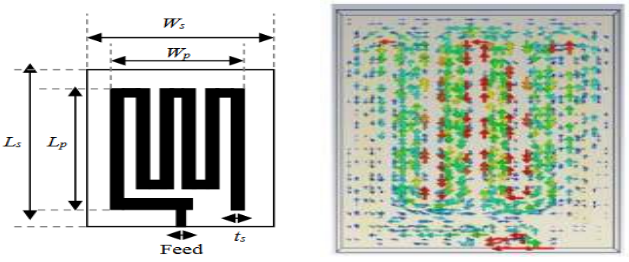
A circularly polarized (CP) helical implantable antenna for ingestible capsule application is proposed in [27]. The antenna operates at 2.4 GHz with a gain of -19.83 dBi and bandwidth of 290 MHz. The 3D capsule model and reflection coefficient of the antenna are given in Fig. 5 [27].



(a)

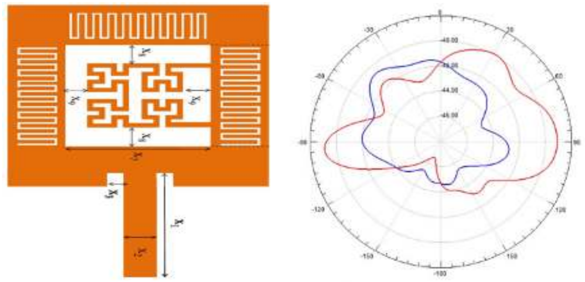
(b)

Fig. 2: (a) Geometry of probe-fed wideband implantable antenna (b) Radiation pattern of the antenna [22].



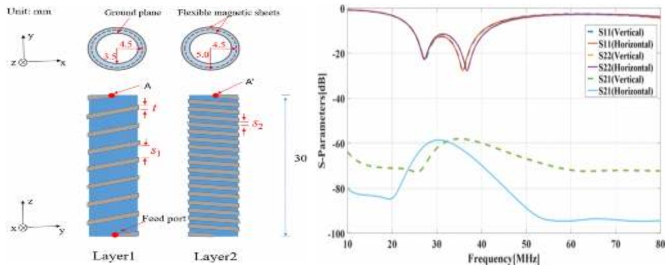
(a) (b)

Fig. 3: (a) Structure implantable meander line antenna (b) Surface current density of the antenna at 402.5 MHz [25].



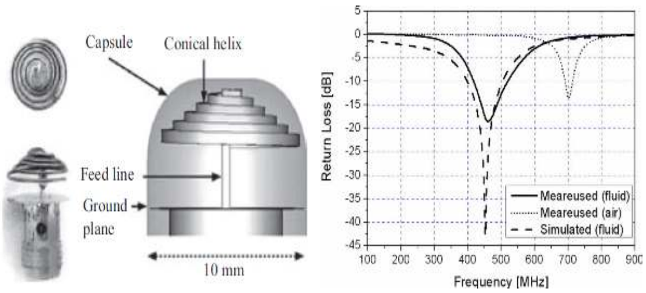
(a) (b)

Fig. 4: (a) Geometry of the implantable fractal patch antenna (b) Radiation pattern of the antenna at 2.45 GHz. [26].



(a) (b)

Fig. 6: (a) Structure of implantable helical antenna using two layers of magnetic sheets (b) Reflection coefficient [28].



(a) (b)

Fig. 7: (a) Conical spiral implantable antenna geometry (b) Reflection coefficient of the antenna [29].

Xin *et al.* have designed a 3 cm long helical antenna in [28]. To achieve the dual resonance, two non-equally spaced helical copper foil layers are used. The antenna is tested in a 28×16×28 cm^3 phantom model with ϵ_r=56.05 and σ=0.52 S/m at 30 MHz. The gain of the antenna is -67 dBi while the impedance bandwidth is 48.21%. Geometry and S11 curve of the antenna are shown in Fig. 6 [28].

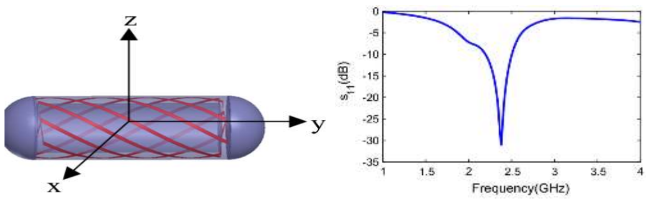
A 50 Ω coaxial probe fed conical spiral antenna operating at 450 MHz with a bandwidth of 10 MHz is presented in [29]. The gain and efficiency of the antenna are not listed. A liquid phantom with ϵ_r=56 and σ=0.83 S/m is used for the measurements. The antenna design and reflection coefficient are shown in Fig. 7 [29].

C. Conformal Antennas

A conformal CP implantable antenna operating at 2.45 GHz and using Rogers RO6010 as substrate with ϵ_r=10.2 and tanδ=0.0023 is discussed in [30]. The size of the antenna is 14.2×16.64×0.254 mm^3. The antenna offers a gain and bandwidth of -29.1 dBi and 31% . The efficiency of antenna is not reported. The antenna is tested using muscle phantom having dimensions of 100×100×100 mm^3 with ϵ_r=52.74 and σ=1.74 S/m. The geometry and reflection coefficient of the antenna are illustrated in Fig. 8 [30].

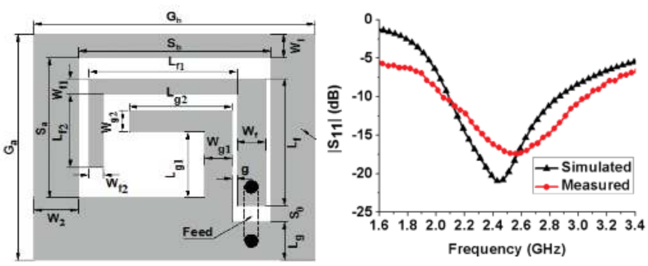
In [31], a conformal patch antenna operating at 2.48 GHz is presented by Ketavath et al. The high permittivity substrate employed has ϵ_r=10.2 with tanδ=0.008 making the overall dimensions of the antenna as 24×22×0.07 mm^3. The antenna gain and bandwidth are -19.7 dBi and 24%. The geometry and S11 of the proposed antenna are illustrated in Fig. 9 [31].

Zhang et al. have proposed a differentially fed antenna for ingestible capsule system in [32]. Polyimide with ϵ_r=3.5 and tanδ=0.008 is used as substrate with thickness of 0.15 mm. The antenna operates at 915 MHz with a gain of -21 dBi and



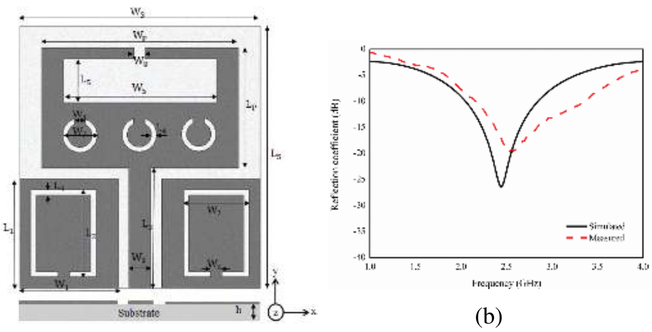
(a) (b)

Fig. 5: (a) Structure of helical antenna for ingestible capsule (b) Reflection coefficient of the antenna [27].



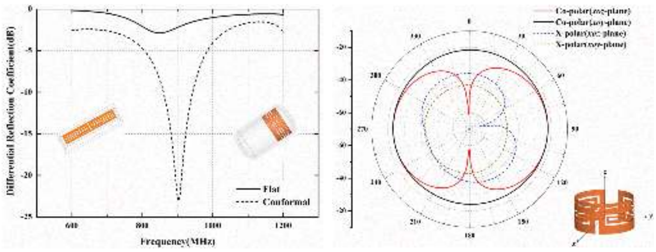
(a) (b)

Fig. 8: (a) Geometry of implantable CP conformal antenna (b) Reflection coefficient of the antenna [30].



(a) (b)

Fig. 9: (a) Geometry of implantable conformal patch antenna (b) S11 curve of the antenna [31].



(a) (b)

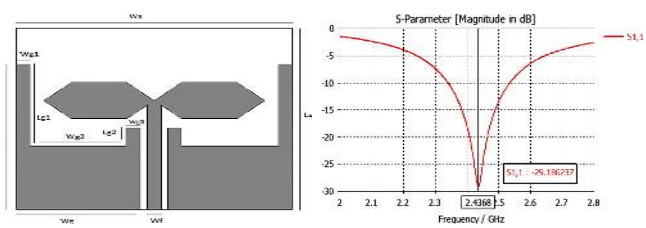
Fig. 10: (a) Reflection coefficient of differentially fed implantable antenna in flat and conformal form (b) Radiation patterns of the antenna at 915 MHz [26].

bandwidth of 8.9%. Efficiency of the antenna is not reported. The reflection coefficient and radiation pattern of the antenna are depicted in Fig. 10 [32].

A hexagon bow-tie patch antenna using Al_2O_3 with ϵ_r=9.8 as substrate operating at 2.45 GHz is proposed by Mahalakshmi et al. in [33] as shown in Fig. 11. The antenna has dimensions of 10×10×1 mm^3 and offers a gain of -14.5 dBi.

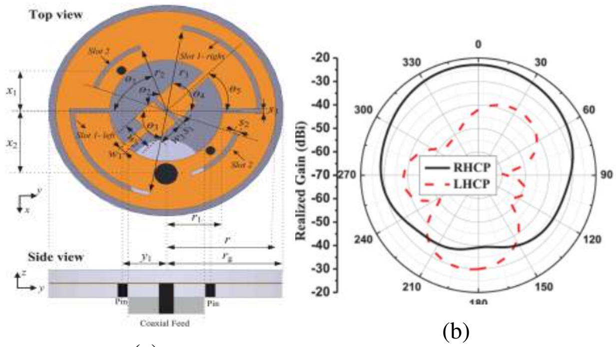
D. Spiral Antennas

A CP ring antenna is proposed by Xu et al. [34]. The antenna operates at 2.45 GHz with a size of π×52×1.27 mm^3. It uses Rogers 3010 with ϵ_r=10.23, tanδ=0.0035 and thickness of 0.635 mm as substrate (Fig. 12). The antenna is tested using muscle tissues with ϵ_r=52.7 and σ=1.74 S/m. It offers a gain of 22.7 dBi and bandwidth of 12.4 %. The efficiency of the antenna is not reported.



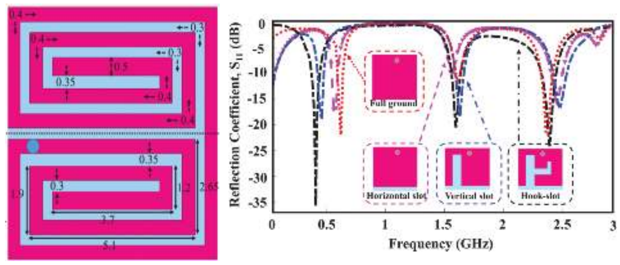
(a) (b)

Fig. 11: (a) Structure of the implantable bow-tie antenna (b) S11 curve of the antenna [33].



(a) (b)

Fig. 12: (a) Top and side view of the implantable CP ring antenna (b) Radiation pattern of the antenna at 2.45 GHz [34].



(a) (b)

Fig. 13: (a) Structure of implantable spiral antenna (b) Reflection coefficient with different ground planes [35].

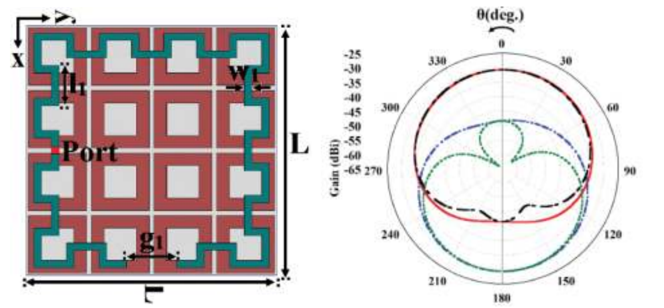
A triband spiral shaped implantable antenna with slotted ground operating at 402 MHz, 1.6 GHz and 2.45 GHz (Fig. 13) is discussed by Shah et al. [35]. The size of the antenna is 7×6.5×0.377 mm^3 while Rogers RT/Duroid 6010 with ϵ_r=10.2 and tanδ=0.0035 is used as superstrate and substrate. The gain of the antenna at the three frequencies is noted to be -30.5 dBi, -22.6 dBi, -18.2 dBi, respectively while it has a bandwidth of 36.8%, 10.8% and 3.4% respectively. Efficiency of the antenna is not reported.

Smantha et al. have proposed a dual band CP antenna having a size of 10×10×0.6 mm^3 in [36]. The antenna is operating at 902 MHz and 2.45 GHz and makes use of Rogers 3010 as reactive impedance substrate with ϵ_r=10.2 and tanδ=0.0035. The antenna gain, bandwidth and efficiency at 920 MHz are -29.33 dBi, 12.2% and 2.6% while these parameters at 2.45 GHz are -21.0 dBi, 123% and 3.8% as given in Fig. 14. Skin mimicking gel is used to test the antenna.

A CP loop antenna is proposed by Xu et al. in [37]. The substrate and superstrate material for this antenna is 0.635 mm Roger 3010 with ϵ_r=10.2 and tanδ =0.0035. The size of the antenna is 13×13×1.27 mm^3 with center frequency of 915 MHz (Fig. 15). The antenna has a gain of -32 dBi and bandwidth of 18.2%. It is tested in skin tissue model, minced pork and skin mimicking gel.

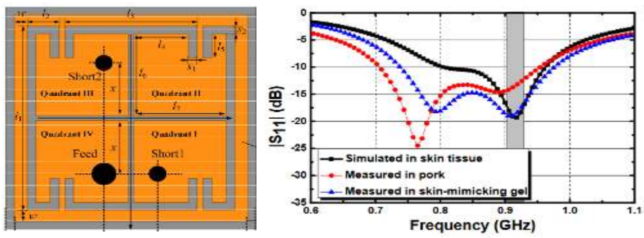
E. Slot Antennas

A coplanar waveguide fed triangular slot antenna is proposed in [38]. The antenna has a size of 10×10×0.65 mm^3



(a) (b)

Fig. 14: (a) Geometry of implantable dual band CP antenna (b) Radiation pattern of the antenna at 920MHz (c) Radiation pattern at 2.45 GHz [36].

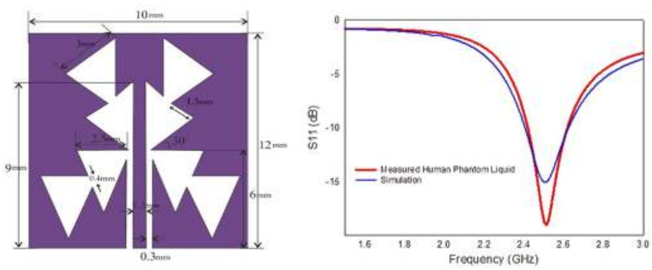


(a) (b)

Fig. 15: (a) Structure of implantable loop antenna (b) Reflection coefficient [37].

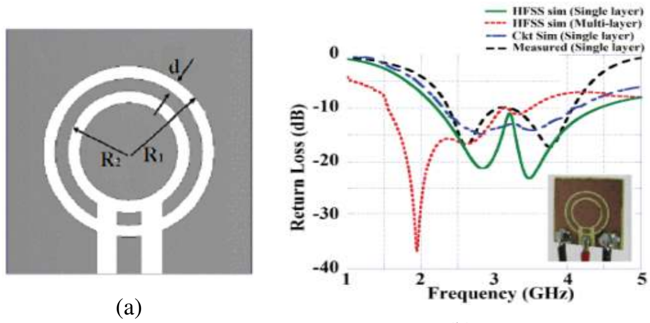
with a resonant frequency of 2.45 GHz as shown in Fig. 16. Al_2O_3 is used as substrate and the antenna is tested in liquid phantom showing a peak gain of -6 dBi and a bandwidth of 8.2%. The radiation efficiency of antenna is 0.4%.

A wideband flexible antenna is presented in [39] by Das et al. The antenna is designed on Kapton polyimide substrate having ϵ_r=2.91 and tan δ=0.005. Rogers 6010 with ϵ_r=10.2 and tanδ=0.0023 is used as superstrate. A metamaterial array is used at the top of the superstrate to enhance the gain. The antenna has dimensions of 10×10×0.4 mm^3 operating at 2.45 GHz as illustrated in Fig. 17. It offers a bandwidth of 57%, a gain of -9 dBi and efficiency of 2.3%. A CP implantable slot antenna operating at 915 MHz is discussed in [40]. The antenna size is 15×15×1.27 mm^3 and it uses Rogers 3010 (ϵ_r=10.2 and tanδ=0.0035) as substrate. Gain of the antenna



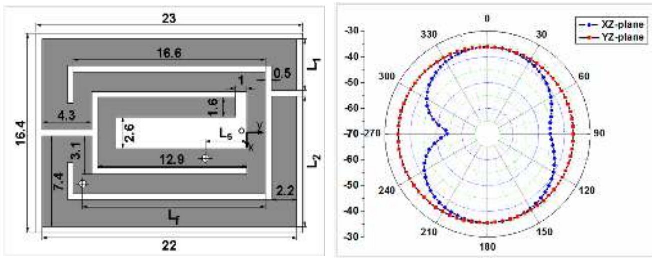
(a) (b)

Fig. 16: (a) Geometry implantable triangular slot antenna (b) Reflection coefficient [38].



(a) (b)

Fig. 17: (a) Geometry of implantable flexible metamaterial antenna (b) Reflection coefficient [39].



(a) (b)

Fig. 18: (a) Geometry of implantable broadband PIFA antenna (b) Radiation pattern of the antenna at 402 MHz [41].

is -27 dBi and it exhibits a bandwidth of 1.53%. The antenna is tested using skin phantom (ϵ_r=41.35 and σ=0.87 S/m).

F. Planar Inverted F Antennas (PIFA)

A compact broadband implantable PIFA having a size of 23×16.4×1.27 mm^3 and operating at 402 MHz is proposed in [41]. The substrate has ϵ_r=10.2 and tanδ=0.0023. A gain of -34.9 dBi and bandwidth of 52 MHz is being achieved by the antenna as sown in Fig. 18.

Luo et al. have designed a PIFA with slotted ground plane in [42]. The antenna makes use of 0.635 mm thick layer of Rogers 3010 (ϵ_r=10.2 and tanδ=0.005) as substrate and superstrate with an overall size of $\pi \times 5.35^2 \times 1.34$ mm^3. The antenna resonates at 402 MHz and 2.45 GHz Fig. 19. The gain and bandwidth of the antenna at 402 MHz are -41 dBi and 41% while these parameters are -21.3 dBi and 27.8% at 2.45 GHz. Minced pork is used for the measurements.

IV. Implantable Antenna Design: Requirements and Challenges

It is established from the discussion in earlier sections that the operation of implantable antennas within the human body is completely different from those of conventional antennas operating in free space. Though, sometimes their design requirements are application dependent, some key design provisions are common and are discussed here in this section.

TABLE I: Comparative analysis of implantable antennas.

Reference	Antenna type	Volume (mm^3)	f_o (GHz)	Gain (dBi)	Bandwidth (%)	η (%)	Substrate
[23]	Flexible antenna	11×11×2	2.42	-20.8	10.4	-	PMDS ϵ_r=2.8
[24]	Patch antenna	8×6×0.5	0.915; 2.45	-28.5; -22.8	9.84; 8.57	-	ϵ_r=10.2; tanδ=0.0023
[26]	patch antenna	11.44×11.44× 0.275	2.45	-	1.5	-	Silicon ϵ_r=11.7
[25]	Meander line antenna	30.5×21.02× 6.4	0.4025	-	33.5	-	FR-4 ϵ_r=4.7; tanδ=0.025
[30]	Conformal CP antenna	14.2× 16.64×0.254	2.45	-29.1	31	-	ϵ_r=10.2; tanδ=0.0022
[31]	Patch antenna	24×22×0.07	2.48	-19.7	24	-	ϵ_r=3.5; tanδ=0.008
[32]	Conformal antenna	34.5×5.8×0.15	0.915	-21	8.9	-	ϵ_r=3.5; tanδ=0.008
[33]	Bow-tie antenna	10×10×1	2.43	-14.5	-	-	Al_2O_3 ϵ_r=9.8; tanδ =0.001
[34]	Ring antenna	π×52×1.27	2.45	-22.7	12.4	-	ϵ_r=10.2; tanδ=0.0035
[35]	Spiral shape	7×6.5×0.377	0.402; 1.6; 2.45	-30.5;-22.6;-18.2	36.8; 10.8; 3.4	-	ϵ_r=10.2; tanδ=0.0035
[36]	Loop antenna	10×10×0.6	0.92; 2.45	-29.33;-21.0	12.2; 123	2.6; 3.8	ϵ_r=10.2; tanδ=0.0035
[37]	Loop antenna	13×13×1.27	0.915	-32	18.2	-	ϵ_r=10.2; tanδ=0.0035
[38]	Triangular slot antenna	10×10×0.65	2.45	7.9	7	0.5	Al_2O_3 ϵ_r=9.8; tanδ =0.001
[39]	Slot antenna	10×10×0.4	2.45	-9	57	2.3	ϵ_r=2.91; tanδ= 0.005
[40]	CP antenna	15×15×1.27	0.915	-27	1.53	-	ϵ_r=10.2; tanδ=0.0022
[41]	PIFA	23×16.4×1.27	0.402	-34.9	0.13	-	ϵ_r=10.2; tanδ=0.0023
[42]	PIFA	π×5.35×1.34	0.402; 2.45	-41; -21.3	41; 27.8	-	ϵ_r=10.2; tanδ=0.005
[43]	CP antenna	11×11×1.27	0.915	-29	1.2	23	ϵ_r=10.2; tanδ=0.0023
[44]	Circular antenna	π×7.52×1.92	0.4035; 0.4339; 2.45	-	28; 10	-	ϵ_r=10.2; tanδ=0.0022
[45]	Flowershape-antenna	7×7.2×0.2	0.928;2.45	-28.44;-25.65	19.8; 8.9	-	ϵ_r=2.9; tanδ=0.0025
[46]	SRR Antenna	10×12×1.27	0.420; 2.45	-	34.5; 58.5	-	ϵ_r=10.2; tanδ=0.0023
[47]	Clover slot antenna	14×12×0.8	2.45	-6	7.3	-	Al_2O_3 ϵ_r=9.8; tanδ =0.001
[48]	Ferrite antenna	10×10×1.28	2.45	-17	-	-	ϵ_r=10.2; tanδ=0.0022
[49]	CP antenna	10×10×1.27	2.45	-22.33	14.03	-	ϵ_r=10.2; tanδ=0.003
[50]	USlot antenna	29×29×0.5	2.45	-	8.5	-	ϵ_r=10.2
[51]	Bowtie antenna	26×22×0.65	2.45	7.7	6	0.2	-
[52]	Monopole antenna	18×24×1	2.4	2.5	-	-	ϵ_r=28
[53]	Meander slot antenna	12.5×14.7×1.27	2.45	16.9	5.7	98	ϵ_r=10.2; tanδ=0.0023

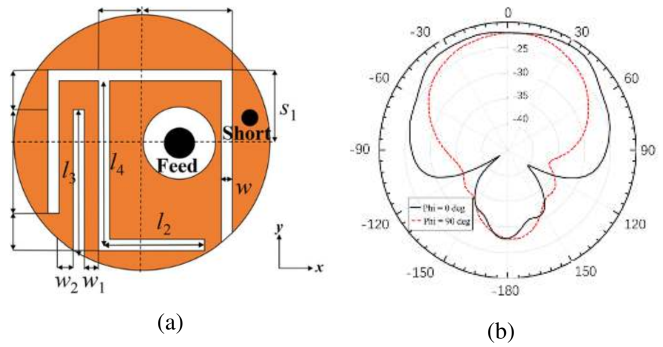


Fig. 19: (a) Structure of implantable PIFA with slotted ground plane (b) Radiation pattern at 2.45 GHz [42].

A. Miniautrization

The implantable antenna is a major component of an implantable device so the miniaturization of the implantable antenna is a very crucial factor. The implantable antennas operate in Medical Implantable Communication Service (MICS) band (402 – 405 MHz), Medical Device Radio Communication Service (MedRadio) band (401 MHz – 406 MHz) and Industrial, Scientific and Medical (ISM) band (902 – 928 MHz) and (2.4 – 2.45 GHz) [54], [55], [56].

There are different miniaturization techniques being employed to reduce the antenna size. Some popular methods are as follows:

1) Use of High Permittivity Dielectric Substrate: Size of the implantable antenna can be reduced by using high permittivity dielectric substrate or high permittivity dielectric superstrate. The high permittivity substrate would result in shorter wavelength which would cause the resonant frequency to be lowered [57]. In [58], Rogers 6002 substrate with relative permittivity of ϵ_r=10.2 is used to reduce the size of the antenna. A very high permittivity substrate, $MgTa_{1.5}Nb_{0.5}O_6$ with relative permittivity of ϵ_r=28. is used for size reduction in [59]. In first case, 14% reduction is achieved while in later case, the size is reduced by 29%. Use of very high permittivity substrate or superstrate can cause the input power of the antenna to be converted into surface waves that affects the radiation efficiency of the antenna.

2) Planar Inverted F Antennas (PIFAs): Planar Inverted F Antenna (PIFA) structures are the easiest way of getting miniaturization for the implantable antennas. Microstrip patch antennas are also used for this purpose. Wavelength of the microstrip patch antenna is half of its resonant length while the wavelength of the PIFA is quarter of its resonant length [60]. So, the PIFAs are preferred over the microstrip patch antennas where the size reduction is needed.

3) Radiator Current Path Lengthening: Lengthening the current path of the radiator is another way of getting size reduction in implantable antennas. An increased current path brings the resonant frequency of the implantable antenna to a lower band [57]. Radiator stacking is an effective technique to lengthen the current path of the radiator in which two radiators are stacked one above the other, either vertically or horizontally [61]. A size reduction of 33% can be achieved through this technique.

4) Inductive/Capacitive Loading: Loading technique can be used to get the impedance matching at the desired frequency of operation. The loading could be inductive or capacitive which would minimize the imaginary part of the impedance helping in the size reduction. Inductive loading technique has been used in [62]. In [63], the capacitive loading technique is used to achieve the size reduction. Using inductive/capacitive loading can result in 72% reduction in the antenna size.

5) Use of Higher Operating Frequency: The easiest way to reduce the size of the antenna is to use a higher operating frequency [1], [64]. If the size of the antenna is reduced, the resonant frequency of the antenna will shift to a higher value and vice versa. The problem with the higher frequency operation is that the losses are more which affect the overall performance of the system. Since, the implantable antennas operate in three frequency bands which are MICS band, MedRadio band and ISM band [65], [66], the MICS band is more commonly used to avoid the increased level of losses.

6) Engineering Ground Plane: Impedance matching plays an important role in the efficient working of the antenna. If the ground plane structure is changed, the impedance matching and hence the size of the antenna changes [67]. One way to achieve that is making a slot in the ground plane to alter the path of return current. This slows the current as the displacement of the current from one edge of the slot to the other causes a phase shift resulting in a smaller antenna size [66].

B. Patient Safety

Implantable medical devices are positioned inside the human body. Careful considerations are therefore, needed to rule out damage to the human body tissues due to electromagnetic exposure. Different precautions are taken to ensure the patient safety as discussed below.

1) Specific Absorption Rate (SAR): Specific Absorption Rate (SAR) is the amount of RF energy absorbed by the human body tissues. It is used as a metric to ensure the safety of biological tissues in the event of electromagnetic exposure. There are two standards for SAR which are internationally adopted. According to IEEE C95.1-1999 standard, the SAR should be less than 1.6 W/kg averaged over 1 g cubic volume of the tissue [68]. The IEEE C95.1-2005 standard specifies that the SAR should be less than 2 W/kg averaged over 10 g cubic volume of the tissue [69]. The FCC uses 1 g averaging while ICNIRP recommends 10 g averaging [70], [71]. 2W/kg over 10 g cubic tissue would be equal to 4-6 W/kg averaged over 1 g cubic tissue. To maintain standard SAR levels, the implantable devices are required to use low output power. Usually the Specific Absorption (SA) per pulse is determined by [72]:

TABLE II: Comparative analysis of antenna miniaturization techniques

Technique	Pros	Cons
High Permittivity Dielectric Substrate	One of the commonly used techniques for size reduction.	Can convert the input power of the antenna into surface waves resulting in lower efficiency.
PIFA Structures	Compact size implantable antenna can be designed using this structure at lower frequencies. PIFA has low backward radiation.	Results in low gain as currents at adjacent arms cancels each other affecting far field radiation.
Current Path Lengthening	Slows the current flow which makes the physically small antenna into an electrically large radiator.	The current on the edges may cancel each other due to phase shift which affects the antenna performance.
High Frequency Use	The easiest technique to reduce the size of the antenna.	The antenna would incur more losses due to interference at higher frequencies.
Inductive /Capacitive Loading	Loading helps in impedance mismatch and minimize frequency shift while keeping size small.	This technique may lead to low antenna gain.
Engineering Ground Plane	Helps in size reduction by creating slots in ground plane.	The radiated signal from the edges of ground slot may lead to electromagnetic compatibility problem if not controlled.

$$SA = SAR \times T_P \quad (1)$$

Where T_p denotes the pulse duration. The electromagnetic power absorbed by the body tissue can raise temperature of the tissue. The temperature of the human body tissue near the implanted device should not increase more than 1-2 ^0C [?].

2) Effective Isotropic Radiated Power (EIRP): A high level of EIRP of the implantable antenna can be harmful to the human body and will interfere with nearby radio devices. The standardized limit of EIRP for an implantable antenna operating in MedRadio band is -16 dBm and -20 dBm for ISM band [?], [8]. If the implantable antenna is used for data telemetry, the input power should be limited to avoid damage to the tissues. If the implantable antenna acts as a receiver, the external source power should adhere to these standards.

C. Biocompatibility

Biocompatibility is also an important factor for implantable antennas to ensure the safety of the human subject. A direct contact of the antenna with the human body tissues would get it short circuited because the body tissues are electrically conductive. Two approaches are used commonly to ensure the biocompatibility. One, is to use the biocompatible material for antenna fabrication and the other, is to encapsulate the antenna with a biocompatible superstrate [73]. Some of the biocompatible materials used for the implantable antenna design are Ceramic Alumina ($\epsilon_r = 9.4; tan\delta = 0.006$), Teflon ($\epsilon_r = 2.1; tan\delta = 0.001$) and

TABLE III: Electric properties of human body tissues at 403 MHz and 2.45 GHz bands [86], [87].

Tissue	Conductivity(S/m)		Permittivity	
	403 MHz	2.45 GHz	403 MHz	2.45 GHz
Small intestine	1.9	3.17	66	54.4
Stomach	1	2.2	67.5	62.1
Colon	0.86	2	62.5	53.8
Skin	0.69	1.46	0.69	38
Muscle	0.79	1.74	57.1	52.7

$MACOR$ ($\epsilon_r = 6.1; tan\delta = 0.005$). However, it is difficult to drill and make round cuts in ceramic substrates [74], [75]. The materials used for biocompatible encapsulation are Zirconia ($\epsilon_r = 29; tan\delta \approx 0$), Silastic MDX-4210 Biomedical-Grade Base Elastomer ($\epsilon_r = 3.3; tan\delta \approx 0$) and PEEK ($\epsilon_r = 3.2; tan\delta = 0.01$) [76], [77], [78]. Zirconia is a better candidate for bio-encapsulation due to its electromagnetic properties. Its loss tangent is very low and permittivity value is very high which helps to reduce power loss by concentrating the near field of antenna inside the capsulation. The advantage of PEEK and Silastic MDX-4210 is that they have simple fabrication and are easy to handle.

D. Implantable Antenna Fabrication Methods

Fabrication of the implantable antennas needs utmost level of care due to their intended usage. There are a number of different fabrication methods being proposed in literature including antennas embroidered on fabric, polymer composites encapsulation, microfluidic antennas, photolithograpy and 3D printed antennas [79], [80], [81]. In [82], conductive fabric was embedded with PDMS. Fabricating the antenna using the conductive fabric along with PDMS (acting as the substrate and a protective encapsulation simultaneously) allows for an easier realization and more robust flexible antenna structure than the conventional fabrication methods. An ultra wideband antenna is fabricated using the same technique to achieve the flexibility and robustness in [83].

V. Human Body Effects on Implantable Antenna

Human body is an integral part of the IMDs. It is very lossy medium where electric properties of the tissues change with the change in operating frequency as given in Table III [1], [78], [84]. The high conductivity and permittivity of the human body tissues causes attenuation loss inside human body which is given by [85], [86]:

$$L_\alpha = 20log_{10}(e^{-\alpha L}) \quad (2)$$

Where $\alpha(Np/m)$ is the attenuation constant and $L(m)$ is the distance travelled by the signal in the human body tissue. The attenuation constant is expressed as [85]:

$$\alpha = \omega\sqrt{\frac{\mu\epsilon}{2}(1 + (\frac{\sigma}{\omega\epsilon})^2 - 1)} \quad (3)$$

Where ω(rad/m) and μ(H/m) are angular frequency and permeability of human body tissue whereas ϵ and σ are permittivity and conductivity, respectively. The permeability and permittivity are complex quantities. Non-magnetic nature of body tissues makes imaginary part of the permeability as zero. Apart from the attenuation loss, losses due to reflections at the boundary between tissues are calculated as [85]:

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \quad (4)$$

$$\Gamma = \frac{\eta2 - \eta1}{\eta2 + \eta1} \quad (5)$$

$$L_r = 20log_{10}(\Gamma) \quad (6)$$

Where Γ is the reflection coefficient at tissue boundary and η is the intrinsic impedance. It can be noted that losses are more at higher frequencies due to which MICS and MedRadio bands are preferred for data transmission by implantable devices. Lower frequencies of ISM band can also be used.

The reflection of the transmitted signal also occurs at the boundary between free space and the outer layer of the skin as both mediums have different impedances and electromagnetic properties. Signal power received by the external receiver is calculated by [1], [57], [88]:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_P - e_P - ML_{TX} - ML_{RX} \quad (7)$$

Where $P(dBm)$ is power, $G(dB)$ is gain and $ML(dB)$ is impedance mismatch loss. L_P(dB) is path loss and e_P(dB) is polarization mismatch loss. Gain of the implantable antennas is usually negative because of the lossy nature of the human body tissues. The path loss can be calculated as follows [89]:

$$L_p = 10nlog(\frac{d}{d_0}) + 10log(\frac{4\pi d_0}{\lambda_0})^2 + S \quad (8)$$

Where n is component of path loss and it depends on the environment. For non line of sight propagation, $n = 3$ is used while for line of sight propagation, $n = 1.5$ is used (for free space propagation, $n = 2$ is used. d_0 is the reference distance, λ(m) is the wavelength and S is the random scatter around the mean. Free space antenna gain G is given as [90]:

$$G = \frac{4\pi U}{P_{in}} \quad (9)$$

Where U is the radiation intensity in watt per unit solid angle. P_{in} is the total input power in watts. The gain of a conductive medium (G_{con}) is given by [91], [92]:

$$G_{con} = \frac{4\pi \Re g^2}{R_{rad}} \quad (10)$$

Where $\Re$ comes from the mean value of Poynting vector, i.e. $P = \frac{1}{2}\Re \boldsymbol{H}^2\ w/m^2$ is the radiation resistance. The intrinsic resistance $R_{intrinsic}$ and g are given as [91], [92]:

$$R_{intrinsic} = \sqrt{\frac{\omega\mu}{2\sigma}} \quad (11)$$

$$g = \frac{|H|de^{\frac{d}{\delta}}}{I_i} \quad (12)$$

$|H|$(A/m) is magnetic field, d is distance in meters, I_i is input current in amperes and δ represents skin depth. It can be seen that if the magnetic field inside the human body increases, the gain of the implantable antenna also increases [91].

A. Human Body Effects on Antenna Radiation Efficiency

Antenna radiation efficiency and antenna radiated power are affected by the loss in the human body tissues. The radiation efficiency of implantable antennas is given as [8]:

$$\eta = \frac{P_{rad}}{P_{source}} \quad (13)$$

Where P_{rad} is the radiated power and P_{source} is the source power. In case of implantable antennas, the source power consists of three power components which are reflected, absorbed and radiated powers ($P_{source} = P_{ref} + P_{abs} + P_{rad}$). Due to the near field coupling in the implantable antennas, the absorbed power is larger than the reflected power which would result in low radiation efficiency and radiated power. The absorbed power is expressed as [8]:

$$P_{abs} = \frac{\omega}{2}\int_v \epsilon_0\epsilon_r|E|^2 dV \quad (14)$$

An increase in the absorbed power also increases the specific absorption rate which affects the antenna radiation efficiency. The SAR is given by [93]:

$$SAR = \frac{P_L}{\rho} = \frac{\sigma|E|^2}{\rho} \quad (15)$$

Where ρ (kg/m^3) is mass density and $E(V/m)$ is electric field. Radiation resistance and loss resistance can be used to represent the radiation efficiency as [88]:

$$\eta = \frac{R_{rad}}{R_{rad} + R_L} \quad (16)$$

Where R_{rad} and R_L are radiation and loss resistances in ohms, respectively. If the antenna radiation resistance increases, the antenna radiation efficiency also increases. The antenna radiation resistance R_{rad} is given by [91]:

$$R_{rad} = \frac{P_{rad}}{I_i^2} \quad (17)$$

It can be noted that the radiation resistance of the antenna depends largely on the antenna radiated power. Hence, the radiation efficiency of the antenna decreases inside the human body tissues because of the coupling between the antenna radiating element and the body tissues. Antenna radiation efficiency can be improved in two ways. One technique is to suppress the surface waves of the antenna by removing little portion of the substrate in patch vicinity [94]. Other method is to apply high permittivity biocompatible superstrate [95]. This would lower the antenna coupling and power absorption inside the human body resulting in an increased radiation efficiency.

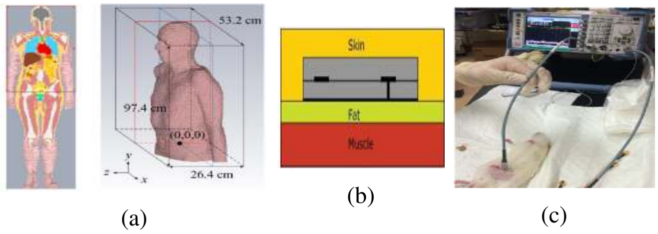


Fig. 20: (a) Three dimensional voxel model (b) A simple three-layer human tissue model (c) Surgical implantation of the antenna into the rat.

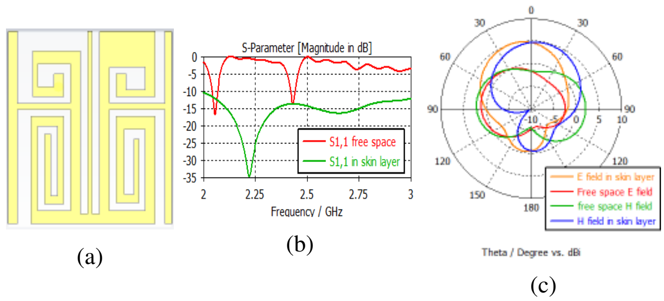


Fig. 21: (a) Proposed rectangular patch antenna (b) S11 curve (c) 3D Radiation pattern.

B. Human Body Effects on Antenna Bandwidth

The implantable antennas are of compact size and exhibit narrow bandwidth. However, all the radiated power does not reach the receiver because of absorption and reflection by the body tissues. The absorbed power is much more than the reflected power for implantable antennas which causes the bandwidth to be wider at the cost of lower radiation efficiency [8]. These losses can be reduced as discussed earlier by using bio-encapsulation and impedance matching making the bandwidth to be narrower. However, the implantable antennas with narrow bandwidth suffer frequency detuning inside the human body. A careful consideration is therefore, needed to be taken to tackle this issue.

The bandwidth of the antenna can be increased by using a thicker substrate. In [96], the bandwidth of a dipole antenna is increased by connecting a small strip line with dipole. In [97], the ground plane of the PIFA is partially connected to RFID circuit to increase the bandwidth.

C. Human Body Effect on Antenna Radiation Pattern

The lossy medium of human body might broaden the radiation pattern due to reflections, refractions and scattering taking place in or from the body tissues [1], [98]. The radiation pattern of an implantable antenna would also be different in the same medium if mounting scenarios and in-body positions differ.

D. Measuring Human Body Effects

Design of implantable antennas is very complicated as they have to operate in complex conditions. Various tools and software are used to design these antennas. To analyze the electromagnetic behavior of the antenna inside the human body, numerical phantoms and tissue models using the Dyadic Green Function expansion method and Finite Difference Time Domain methods are used [99] as shown in Fig. 20(a),(b) [100]. Measurements of the fabricated antenna prototypes usually involves in-vivo testing employing animal tissues such as a rat as shown in Fig. 20(c) [101].

TABLE IV: Comparison of proposed antenna with previous works

Ref.	Size (mm^3)	Freq. (GHz)	Gain (dBi)
[23]	11×11×2	2.42	-20.8
[24]	8×6×0.5	0.915; 2.45	-28.5; -22.8
[30]	14.2×16.64×0.254	2.45	-29.1
[31]	24×22×0.07	2.48	-19.7
This work	6×5×0.5	2.43	5

VI. Design of a Miniaturized Implantable Antenna

Initial results of a novel antenna design are presented that attempts to meet implantable antenna requirements. A patch structure is selected due to its advantages of ease of design and integration. The 50Ω microstrip line fed antenna makes use of a slotted structure to lengthen the current path and hence, attain a small size of 6×5×0.5 mm^3 having Rogers RT6010 (ϵ_r=10.2; tanδ=0.0023) as substrate and superstrate (Fig. 21(a)). The antenna is simulated in skin layer. It operates at 2.43 GHz band with good impedance matching and wide bandwidth (Fig. 21(b)). It exhibits a near-omnidirectional pattern and offers a gain of 5 dBi (Fig. 21(c)).

The proposed antenna is compared with four previous works published in open literature. Comparative study in terms of size, operating frequency and gain is summarised in Table IV. It is evident from this comparison that the proposed antenna exhibits smaller size and higher gain. This along with the presented results showing good radiation pattern and wider bandwidth show that the proposed novel structure has good potential to be used in a miniaturized implantable device. Since it is an ongoing study and antenna has not been fabricated yet, measurement results are not included.

VII. Conclusion

In this paper, a comprehensive review on implantable antennas used for biomedical applications is presented. Since, the antenna is a key component of a bio-sensor operating in a harsh in-body environment, its design becomes a very challenging task. Several factors need to be considered while designing such an antenna including size, gain, efficiency, radiation pattern and patient safety. A detailed critical review is conducted into different implantable antenna designs available in open literature including planar, wire, conformal, spiral, slotted and PIFA structures. Though, the selection of antenna type is generally application specific, patch structures have exhibited greater potential of meeting most of the requirements efficiently.

We have then summarized the key requirements and challenges in implantable antenna design in terms of miniaturization, patient safety and biocompatibility as well as different techniques employed to meet these requirements. Widely used miniaturization methods include using high permittivity substrates, PIFAs, larger current path on the radiator, inductive or capacitive loading, higher operating frequencies and altered ground plane. Each method has been evaluated for its merits and demerits. A detailed comparative study has shown that despite having greater potential of miniaturization, use of higher frequencies suffer from higher losses. However, further investigations are required in this direction as exposure studies at these frequencies are not yet fully established. Patient safety is paramount in implantable devices and it is strictly governed through SAR and EIRP limits. Implantable antennas are bound to meet these regulations and further ensures the safety through use of biocompatible materials. Human body effects on these antennas make it pertinent to consider the human body as part of the antenna design. The paper concludes with introducing initial results of an efficient miniaturized antenna design for implantable devices that tries to meet the requirements discussed in earlier sections.

References

[1] Qammer H. Abbasi, Masood Ur-Rehman, Khalid Qaraqe, and Akram Alomainy. Advances in body-centric wireless communication: Applications and state-of-the-art. *the IET, (UK)*, 2016.

[2] Masood Ur-Rehman, Michael Adekanye, and Hassan Tariq Chattha. Tri-band millimetre-wave antenna for body-centric networks. *Nano Communication Networks*, 18:72–81, 2018.

[3] Konstantina S Nikita. *Handbook of biomedical telemetry*. Wiley Online Library, 2014.

[4] Erdem Topsakal, Maysam Ghovanloo, and Rizwan Bashirullah. Guest editorial: IEEE AWPL special cluster on wireless power and data telemetry for medical applications. *IEEE Antennas and Wireless Propagation Letters*, 11:1638–1641, 2012.

[5] JC Lin and Yu-Jin Wang. An implantable microwave antenna for interstitial hyperthermia. *Proceedings of the IEEE*, 75(8):1132–1133, 1987.

[6] Saket Karajgikar, Smitha Rao, Jeongsik Sin, Dereje Agonafer, Jung-Chih Chiao, Dan Popa, and Harry Stephanou. Electro-thermal analysis of in-plane micropump. *IEEE Transactions on Components and Packaging Technologies*, 33(2):329–339, 2010.

[7] Ayesha Ahmed, Tahera Kalsoom, Masood Ur-Rehman, Naeem Ramzan, Sajjad Karim, and Qammer H. Abbasi. Design and study of a small implantable antenna design for blood glucose monitoring. *ACES Journal*, 33(10), October 2018.

[8] Francesco Merli. Implantable antennas for biomedical applications. Technical report, EPFL, 2011.

[9] William G Scanlon, Noel E Evans, and Zita M McCreesh. Rf performance of a 418-mhz radio telemeter packaged for human vaginal placement. *IEEE transactions on biomedical engineering*, 44(5):427–430, 1997.

[10] Dick Wessels. Implantable pacemakers and defibrillators: device overview & emi considerations. In *2002 IEEE International Symposium on Electromagnetic Compatibility*, volume 2, pages 911–915. IEEE, 2002.

[11] KS Guillory and RA Normann. A 100-channel system for real time detection and storage of extracellular spike waveforms. *Journal of neuroscience methods*, 91(1-2):21–29, 1999.

[12] Thomas Buchegger, Gerald Oßberger, Alexander Reisenzahn, Erwin Hochmair, Andreas Stelzer, and Andreas Springer. Ultra-wideband transceivers for cochlear implants. *EURASIP Journal on Advances in Signal Processing*, 2005(18):647310, 2005.

[13] Mark C Shults, Rathbun K Rhodes, Stuart J Updike, Barbara J Gilligan, and William N Reining. A telemetry-instrumentation system for monitoring multiple subcutaneously implanted glucose sensors. *IEEE Transactions on Biomedical Engineering*, 41(10):937–942, 1994.

[14] Keyoor Gosalia, Gianluca Lazzi, and Mark Humayun. Investigation of a microwave data telemetry link for a retinal prosthesis. *IEEE Transactions on Microwave Theory and Techniques*, 52(8):1925–1933, 2004.

[15] Xiaodong Yang, Dou Fan, Aifeng Ren, Nan Zhao, Syed Aziz Shah, Akram Alomainy, Masood Ur-Rehman, and Qammer H Abbasi. Diagnosis of the hypopnea syndrome in the early stage. *Neural Computing and Applications*, 32(3):855–866, 2020.

[16] Qing Zhang, Daniyal Haider, Weigang Wang, Syed Aziz Shah, Xiaodong Yang, and Qammer H Abbasi. Chronic obstructive pulmonary disease warning in the approximate ward environment. *Applied Sciences*, 8(10):1915, 2018.

[17] Mohsen Zaeimbashi, Hwaider Lin, Cunzheng Dong, Xianfeng Liang, Mehdi Nasrollahpour, Huaihao Chen, Neville Sun, Alexei Matyushov, Yifan He, Xinjun Wang, et al. Nanoneurorfid: A wireless implantable device based on magnetoelectric antennas. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 3(3):206–215, 2019.

[18] Yunxiao Peng, Kazuyuki Saito, and Koichi Ito. Dual-band antenna design for wireless capsule endoscopic image transmission in the mhz band based on impulse radio technology. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 3(3):158–164, 2019.

[19] Yi Fan, Jinhong Huang, Tianhai Chang, and XiongYing Liu. A miniaturized four-element mimo antenna with ebg for implantable medical devices. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 2(4):226–233, 2018.

[20] OK Hammouda and AM Allam. Utilizing implanted antennas to detect the presence of oral cancers. *Res. J. Eng. Sci.*, 2278:9472, 2014.

[21] Zhibin Xiao, Xi Tan, Xianliang Chen, Sizheng Chen, Zijian Zhang, Hualei Zhang, Junyu Wang, Yue Huang, Peng Zhang, Lirong Zheng, et al. An implantable rfid sensor tag toward continuous glucose monitoring. *IEEE journal of biomedical and health informatics*, 19(3):910–919, 2015.

[22] Komal Jaiswal, Ankit Kumar Patel, Shekhar Yadav, Sweta Singh, Ram Suchit Yadav, and Rajeev Singh. Probe-fed wideband implantable microstrip patch antenna for biomedical and telemetry applications. In *Soft Computing and Signal Processing*, pages 635–642. Springer, 2019.

[23] Yusheng Fu, Jianmin Lei, Xiao Zou, and Jiuchuan Guo. Flexible antenna design on pdms substrate for implantable bioelectronics applications. *Electrophoresis*, 40(8):1186–1194, 2019.

[24] Syed Ahson Ali Shah and Hyoungsuk Yoo. Scalp-implantable antenna systems for intracranial pressure monitoring. *IEEE Transactions on Antennas and Propagation*, 66(4):2170–2173, 2018.

[25] NH Sulaiman1 NA Samsuri, MKA Rahim, FC Seman, and M Inam. Compact meander line telemetry antenna for implantable pacemaker applications. *Indonesian Journal of Electrical Engineering and Computer Science*, 10(3):883–889, 2018.

[26] Santanu Maity, Kuheli Roy Barman, and Shankar Bhattacharjee. Silicon-based technology: Circularly polarized microstrip patch antenna at ism band with miniature structure using fractal geometry for biomedical application. *Microwave and Optical Technology Letters*, 60(1):93–101, 2018.

[27] Saber Helmy Zainud-Deen, Hend Abd El-Azem Malhat, and Asmaa Adel Balabel. Octafilar helical antenna for circular polarization wireless capsule endoscopy applications. *Wireless Personal Communications*, pages 1–11, 2019.

[28] Xin Wang, Jingjing Shi, Lisheng Xu, and Jianqing Wang. A wideband miniaturized implantable antenna for biomedical application at hbc band. In *2018 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, pages 1–3. IEEE, 2018.

[29] Sang Heun Lee, Kihun Chang, Ki Joon Kim, and Young Joong Yoon. A conical spiral antenna for wideband capsule endoscope system. In *2008 IEEE Antennas and Propagation Society international symposium*, pages 1–4. IEEE, 2008.

[30] Rongqiang Li, Yong-Xin Guo, and Guohong Du. A conformal circularly polarized antenna for wireless capsule endoscope systems. *IEEE Transactions on Antennas and Propagation*, 66(4):2119–2124, 2018.

[31] Kumar Naik Ketavath, Dattatreya Gopi, and Sriram Sandhya Rani. In-vitro test of miniaturized cpw-fed implantable conformal patch antenna at ism band for biomedical applications. *IEEE Access*, 7:43547–43554, 2019.

[32] Ke Zhang, Changrong Liu, Xueguan Liu, Honglong Cao, Yudi Zhang, Xinmi Yang, and Huiping Guo. A conformal differentially fed antenna for ingestible capsule system. *IEEE Transactions on Antennas and Propagation*, 66(4):1695–1703, 2018.

[33] N Mahalakshmi and A Thenmozhi. Design of hexagon shape bow-tie patch antenna for implantable bio-medical applications. *Alexandria engineering journal*, 56(2):235–239, 2017.

[34] Li-Jie Xu, Yaming Bo, Wen-Jun Lu, Lei Zhu, and Cheng-Fei Guo. Circularly polarized annular ring antenna with wide axial-ratio bandwidth for biomedical applications. *IEEE Access*, 7:59999–60009, 2019.

[35] Izaz Ali Shah, Muhammad Zada, and Hyoungsuk 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*, 67(6):4230–4234, 2019.

[36] Gopinath Samanta and Debasis Mitra. Dual-band circular polarized flexible implantable antenna using reactive impedance substrate. *IEEE Transactions on Antennas and Propagation*, 67(6):4218–4223, 2019.

[37] Li-Jie Xu, Yong-Xin Guo, and Wen Wu. Miniaturized circularly polarized loop antenna for biomedical applications. *IEEE Transactions on Antennas and Propagation*, 63(3):922–930, 2015.

[38] Srinivasan Ashok Kumar and Thangavelu Shanmuganantham. Coplanar waveguide-fed ism band implantable crossed-type triangular slot antenna for biomedical applications. *International Journal of Microwave and Wireless Technologies*, 6(2):167–172, 2014.

[39] Soumyadeep Das and Debasis Mitra. A compact wideband flexible implantable slot antenna design with enhanced gain. *IEEE Transactions on Antennas and Propagation*, 66(8):4309–4314, 2018.

[40] Huiying Zhang, Long Li, Changrong Liu, Yong-Xin Guo, and Sirao Wu. Miniaturized implantable antenna integrated with split resonate rings for wireless power transfer and data telemetry. *Microwave and Optical Technology Letters*, 59(3):710–714, 2017.

[41] Rongqiang Li, Bo Li, Guohong Du, Xiaofeng Sun, and Haoran Sun. A compact broadband antenna with dual-resonance for implantable devices. *Micromachines*, 10(1):59, 2019.

[42] Lingzhi Luo, Bing Hu, Jiahui Wu, Tianwen Yan, and Li-Jie Xu. Compact dual-band antenna with slotted ground for implantable applications. *Microwave and Optical Technology Letters*, 61(5):1314–1319, 2019.

[43] Changrong Liu, Yudi Zhang, and Xueguan Liu. Circularly polarized implantable antenna for 915 mhz ism-band far-field wireless power transmission. *IEEE Antennas and Wireless Propagation Letters*, 17(3):373–376, 2018.

[44] Abdelrahman E Mohamed, Mohammad S Sharawi, and Ali Muqaibel. Implanted dual-band circular antenna for biomedical applications. *Microwave and Optical Technology Letters*, 60(5):1125–1132, 2018.

[45] Farooq Faisal and Hyoungsuk Yoo. A miniaturized novel-shape dual-band antenna for implantable applications. *IEEE Transactions on Antennas and Propagation*, 67(2):774–783, 2018.

[46] Huiying Zhang, Long Li, Changrong Liu, Yong-Xin Guo, and Sirao Wu. Miniaturized implantable antenna integrated with split resonate rings for wireless power transfer and data telemetry. *Microwave and Optical Technology Letters*, 59(3):710–714, 2017.

[47] S Ashok Kumar and T Shanmuganantham. Design of clover slot antenna for biomedical applications. *Alexandria engineering journal*, 56(3):313–317, 2017.

[48] Maxwell Fazeli, Yang-Ki Hong, Woncheol Lee, and Jihoon Park. Implantable ferrite antenna for biomedical applications. *Microwave and Optical Technology Letters*, 58(11):2745–2749, 2016.

[49] Hua Li, Yong-Xin Guo, and Shao-Qiu Xiao. Broadband circularly polarised implantable antenna for biomedical applications. *Electronics Letters*, 52(7):504–506, 2016.

[50] S Ashok Kumar, T Shanmuganantham, and G Sasikala. Design and development of implantable cpw fed monopole u slot antenna at 2.45 ghz ism band for biomedical applications. *Microwave and Optical Technology Letters*, 57(7):1604–1608, 2015.

[51] S Ashok Kumar and T Shanmuganantham. Design and analysis of implantable cpw fed bowtie antenna for ism band applications. *AEU-International Journal of Electronics and Communications*, 68(2):158–165, 2014.

[52] S Ashok Kumar and T Shanmuganantham. Implanted cpw fed monopole antenna for biomedical applications. In *Advances in Computing and Information Technology*, pages 97–105. Springer, 2013.

[53] Xuyang Li, Malyhe Jalilvand, Wendy You, Werner Wiesbeck, and Thomas Zwick. An implantable stripline-fed slot antenna for biomedical applications. 2013.

[54] Amandeep Chauhan, Gurveer Kaur Chauhan, and Gurpreet Kaur. Implantable antennas in biomedical applications. In *2015 International Conference on Computational Intelligence and Communication Networks (CICN)*, pages 25–29. IEEE, 2015.

[55] Safety Code. 6, limits of human exposure to radiofrequency electromagnetic fields in the frequency range from 3 khz to 300 ghz. *Health Canada*, 1999.

[56] Asimina Kiourti, Andromachi Kaltampani, and Konstantina S Nikita. A novel algorithm for implantable antenna design: Size and radiation performance considerations. In *The 8th European Conference on Antennas and Propagation (EuCAP 2014)*, pages 864–867. IEEE, 2014.

[57] Asimina Kiourti and Konstantina S Nikita. A review of implantable patch antennas for biomedical telemetry: Challenges and solutions [wireless corner]. *IEEE Antennas and Propagation Magazine*, 54(3):210–228, 2012.

[58] Pichitpong Soontornpipit, Cynthia M Furse, and You Chung Chung. Miniaturized biocompatible microstrip antenna using genetic algorithm. *IEEE Transactions on Antennas and Propagation*, 53(6):1939–1945, 2005.

[59] Tsung-Fu Chien, Chien-Min Cheng, Hung-Chi Yang, Jian-Wei Jiang, and Ching-Hsing Luo. Development of nonsuperstrate implantable low-profile cpw-fed ceramic antennas. *IEEE Antennas and Wireless Propagation Letters*, 9:599–602, 2010.

[60] Jaehoon Kim and Yahya Rahmat-Samii. Implanted antennas inside a human body: Simulations, designs, and characterizations. *IEEE Transactions on microwave theory and techniques*, 52(8):1934–1943, 2004.

[61] Asimina Kiourti, Maria Christopoulou, and Konstantina S Nikita. Performance of a novel miniature antenna implanted in the human head for wireless biotelemetry. In *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*, pages 392–395. IEEE, 2011.

[62] Li-Jie Xu, Yong-Xin Guo, and Wen Wu. Bandwidth enhancement of an implantable antenna. *IEEE Antennas and Wireless Propagation Letters*, 14:1510–1513, 2014.

[63] Changrong Liu, Yong-Xin Guo, and Shaoqiu Xiao. Capacitively loaded circularly polarized implantable patch antenna for ism band biomedical applications. *IEEE transactions on antennas and propagation*, 62(5):2407–2417, 2014.

[64] Masood Ur-Rehman, Nabeel Ahmed Malik, Xiaodong Yang, Qammer H. Abbasi, Zhiya Zhang, and Nan Zhao. A low profile antenna for millimeter-wave body-centric applications. *IEEE Transactions on Antennas and Propagation*, 65(12):6329–6337, Dec 2017.

[65] Tutku Karacolak, Aaron Z Hood, and Erdem 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*, 56(4):1001–1008, 2008.

[66] Wei Xia, Kazuyuki Saito, Masaharu Takahashi, and Koichi Ito. Performances of an implanted cavity slot antenna embedded in the human arm. *IEEE Transactions on Antennas and Propagation*, 57(4):894–899, 2009.

[67] Layla Wakrim, Saida Ibnyaich, and Moha M'rabet Hassani. The study of the ground plane effect on a multiband pifa antenna by using genetic algorithm and particle swarm optimization. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 15(4):293–308, 2016.

[68] Federal Communications Commission et al. Medical implant communications service (mics) federal register. *Rules Reg*, 64(240):69926–69934, 1999.

[69] James C Lin. Safety standards for human exposure to radio frequency radiation and their biological rationale. *IEEE Microwave Magazine*, 4(4):22–26, 2003.

[70] Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields. *FCC*, 1997.

[71] ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). *ICNIRP website, http://www.icnirp.de/documents/emfgdl.pdf)*.

[72] Changrong Liu, Yong-Xin Guo, and Shaoqiu Xiao. A review of implantable antennas for wireless biomedical devices. In *Forum for electromagnetic research methods and application technologies (FERMAT)*, 2015.

[73] Pichitpong Soontornpipit, Cynthia M Furse, and You Chung Chung. Design of implantable microstrip antenna for communication with medical implants. *IEEE Transactions on Microwave theory and techniques*, 52(8):1944–1951, 2004.

[74] Ruchi Warty, Mohammad-Reza Tofighi, Usmah Kawoos, and Arye Rosen. Characterization of implantable antennas for intracranial pressure monitoring: Reflection by and transmission through a scalp phantom. *IEEE Transactions on Microwave Theory and Techniques*, 56(10):2366–2376, 2008.

[75] Tutku Karacolak, Robert Cooper, James Butler, Stephen Fisher, and Erdem Topsakal. In vivo verification of implantable antennas using rats as model animals. *IEEE Antennas and Wireless Propagation Letters*, 9:334–337, 2010.

[76] Anja K Skrivervik and Francesco Merli. Design strategies for implantable antennas. In *2011 Loughborough Antennas & Propagation Conference*, pages 1–5. IEEE, 2011.

[77] Javier Abadia, Francesco Merli, Jean-Francois Zurcher, Juan R Mosig, and Anja K Skrivervik. 3d-spiral small antenna design and realization for biomedical telemetry in the mics band. *Radioengineering*, 18(4):359–367, 2009.

[78] D Andreuccetti, R Fossi, and C Petrucci. An internet resource for the calculation of the dielectric properties of body tissues, 2002.

[79] Bahare Mohamadzade, Raheel M Hashmi, Roy BVB Simorangkir, Reza Gharaei, Sabih Ur Rehman, and Qammer H Abbasi. Recent advances in fabrication methods for flexible antennas in wearable devices: State of the art. *Sensors*, 19(10):2312, 2019.

[80] Karu P Esselle, Basit A Zeb, Raheel Hashmi, and Roy BVB Simorangkir. Antennas for wireless medical devices. In *Antennas for small mobile terminals*, pages 183–202. Artech House, 2018.

[81] Anindya Nag, Roy BVB Simorangkir, Elizabeth Valentin, Toni Björninen, Leena Ukkonen, Raheel M Hashmi, and Subhas Chandra Mukhopadhyay. A transparent strain sensor based on pdms-embedded conductive fabric for wearable sensing applications. *IEEE Access*, 6:71020–71027, 2018.

[82] Roy BVB Simorangkir, Yang Yang, Raheel M Hashmi, Toni Björninen, Karu P Esselle, and Leena Ukkonen. Polydimethylsiloxane-embedded conductive fabric: Characterization and application for realization of robust passive and active flexible wearable antennas. *IEEE Access*, 6:48102–48112, 2018.

[83] Bahare Mohamadzade, Roy BVB Simorangkir, Raheel M Hashmi, and Ali Lalbakhsh. Communication a conformal ultrawideband antenna with monopole-like radiation patterns. *IEEE Transactions on Antennas and Propagation*, 2020.

[84] Masood Ur-Rehman, Yue Gao, Zhao Wang, J. Zhang, Yasir Alfadhl, Xiaodong Chen, Clive G. Parini, Zhinong Ying, and Thomas Bolin. Investigation of on-body bluetooth transmission. *IET Microwaves, Antennas Propagation*, 4(7):871–880, 2010.

[85] Asimina Kiourti and Konstantina S Nikita. Miniature scalp-implantable antennas for telemetry in the mics and ism bands: design, safety considerations and link budget analysis. *IEEE Transactions on Antennas and Propagation*, 60(8):3568–3575, 2012.

[86] S. Gabriel, R. W. Lau, and C. Gabriel. The dielectric properties of biological tissues: II. measurements in the frequency range 10 Hz to 20 GHz. *Physics in Medicine and Biology*, 41(11):2251–2269, 1996.

[87] Dielectric properties. *ITIS website, http://http://www.itis.ethz.ch/virtual-population/tissue-properties/database/dielectric-properties).*

[88] Akram Alomainy and Yang Hao. Modeling and characterization of biotelemetric radio channel from ingested implants considering organ contents. *IEEE Transactions on Antennas and Propagation*, 57(4):999–1005, 2009.

[89] Yi Huang and Kevin Boyle. *Antennas: from theory to practice*. John Wiley & Sons, 2008.

[90] R Moore. Effects of a surrounding conducting medium on antenna analysis. *IEEE Transactions on Antennas and Propagation*, 11(3):216–225, 1963.

[91] C Tsao. Radiation resistance of antennas in lossy media. *IEEE Transactions on Antennas and Propagation*, 19(3):443–444, 1971.

[92] R. Moore. Effects of a surrounding conducting medium on antenna analysis. *IEEE Transactions on Antennas and Propagation*, 11(3):216–225, 1963.

[93] T Wittig. Sar overview. *CST User Manual*, 2007.

[94] Homayoon Oraizi and Bahram Rezaei. Improvement of antenna radiation efficiency by the suppression of surface waves. *Journal of Electromagnetic Analysis and Applications*, 3(03):79, 2011.

[95] Denys Nikolayev, Maxim Zhadobov, Pavel Karban, and Ronan Sauleau. Increasing the radiation efficiency and matching stability of in-body capsule antennas. In *2016 10th European Conference on Antennas and Propagation (EuCAP)*, pages 1–5. IEEE, 2016.

[96] Shahidul M Islam, Karu P Esselle, David Bull, and Paul M Pilowsky. Bandwidth enhancement of an implantable rfid tag antenna at 900 mhz ism band for rf telemetry. In *2012 International Symposium on Communications and Information Technologies (ISCIT)*, pages 741–745. IEEE, 2012.

[97] Chiu-Yueh Huang, Chi-Lin Tsai, and Chin-Lung Yang. Compact broadband implantable monopole antenna with gain enhancement. In *2014 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, pages 1590–1591. IEEE, 2014.

[98] Masood Ur-Rehman, Qammer H. Abbasi, Muhammad Akram, and Clive Parini. Design of band-notched ultra wideband antenna for indoor and wearable wireless communications. *IET Microwaves, Antennas and Propagation*, 9:243–25, February 2015.

[99] Masood Ur-Rehman, Qammer H. Abbasi, Xiaodong Chen, and Zhinong Ying. Numerical modelling of human body for bluetooth body-worn applications. *Progress In Electromagnetics Research*, 143:623–639, 2013.

[100] Usmah Kawoos, Mohammad-Reza Tofighi, Ruchi Warty, Francis A Kralick, and Arye Rosen. In-vitro and in-vivo trans-scalp evaluation of an intracranial pressure implant at 2.4 ghz. *IEEE Transactions on Microwave Theory and Techniques*, 56(10):2356–2365, 2008.

[101] Changrong Liu, Yong-Xin Guo, Rangarajan Jegadeesan, and Shaoqiu Xiao. In vivo testing of circularly polarized implantable antennas in rats. *IEEE Antennas and Wireless Propagation Letters*, 14:783–786, 2014.

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