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Medical Implantable Antennas for IoT Based Health Monitoring Applications: A Review

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ABSTRACT

Recently, implantable antennas have gained prominence in biomedical research owing to their compact design and efficient performance and extensive potential in biomedical and wireless communication applications. One such application is in the biomedical field, where the designed system must function within human body tissues and interact with an external device. To implement this communication framework, both advanced software and proper hardware design are essential. The antenna that is designed for biomedical applications must fulfill several requirements including energy efficiency, compact size, and multi-band operations. Therefore, designing an antenna with large bandwidth, multiband capability, circular polarization, and a compact size is essential for medical applications. From that point of view, this paper aims to survey existing antenna designs in literature for implantable medical devices (IMDs). The review conducted in this paper will specifically focus on three types of implantable antennas which are dual-band, circular polarized, and multi-band circular polarized antennas. Besides, we analyze the results of the most recently published articles and compare them with existing literature. The key challenges faced in implantable antenna design will also be discussed in detail.

Keywords: Circular-polarized antenna, Dual-band antenna, IMD, Implantable antenna.

1. INTRODUCTION

Our communication method has been shaped by the Internet since a couple of decades ago. Due to lowering the manufacturing cost, compact-sized Internet-enabled smart devices have appeared over the past few years. The concept of the Internet of Things (IoT) is generally defined as a driving force to make the surrounding- objects smart. The primary purpose of IoT technology is to introduce plug and play devices that deliver easy access and remotely controlled experiences to the end-users. Future communication networks will be enriched mainly due to the wide range of services provided by IoT applications. Large capacity, high

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bandwidth, , and short latency are the basic technical requirements to bring these services into reality **(Misra et al., 2016; Pawar and Trivedi, 2019; Kumar and Jamwal, 2021; Chen, 2024)**.

In addition to the above-mentioned requirements, compact size is particularly important to realize IoT devices **(Xu et al., 2014; Khan et al., 2016)**. The study was conducted in **(Bekasiewicz and Koziel, 2016)** states that the number of connected devices has developed significantly during the past decade, and the trend is expected to continue, reaching 50 billion devices in the near future. Due to the nature of their applications, in addition to their compact size, these connected devices have to operate in a multi-band fashion. This poses a severe challenge for the manufacturers as each radio band (i.e., 900MHz, 2.4GHz, and 5GHz) may require various antenna structures to enable the communication **(Wang et al., 2019; Al-Sehemi et al., 2020; Anchidin et al., 2023)**. Therefore, having only sophisticated software is not enough; efficient hardware design plays a central role in manufacturing IoT devices. Thus, different aspects of the antenna, such as size, cost, and power consumption, need to be optimized when it is designed for IoT-based applications. **(Mehmood et al., 2017)**.

Intensive research has been conducted on the new methodologies applied in IoT devices. Some of these include smart mobile system **(Hamza et al., 2016; Awl et al., 2019; Rashid and Al-Hindawi, 2019; Ali and Al-Hindawi, 2021; Ahmed and Al-Hindawi, 2023; Karim and Ali, 2023)** and modern wearable communications **(Tetik and Antepli, 2018; Li et al., 2019; Yadav et al., 2020; Hamza and Al-Hindawi, 2021; Ahmed and Al-Hindawi, 2023; Karim et al., 2023)**.

IoT technology can realize several critical real-world implementations, including AR, autonomous systems, telemedicine procedures, and healthcare monitoring systems. Implantable Medical Devices (IMDs) are considered a central part of IoT based healthcare monitoring systems. IMDs are devices inserted into a person's body for health monitoring, and the antenna used in these devices is known as an implantable antenna. **(Wang et al., 2021; Mosavinejad et al., 2022)**. Cardiac pacemaker is considered to be the first implantable biomedical device **(Greatbatch and Holmes, 1991)**. As the population grows and public awareness of health issues rises, IMDs have gained considerable attention from both manufacturers and research communities. IMDs provide various health-related services, such as temperature measurement **(Scanlon et al., 1997)**, continuous monitoring of glucose **(Yilmaz et al., 2008)**, detection of congestive heart failure (CHF) **(Chow et al., 2009)**, and pacemaker **(Wessels, 2002)**. Continuous health monitoring of patients can be accomplished using IMDs that are capable of communicating with external devices. **(Patil and Rufus, 2020)**. In other words, IMDs is able to monitor the internal status of the patients and send corresponding information to the external equipment (receiver located at outside the body of the patients). To realize such a communication paradigm, IMD is in need for microwave sensors known as implantable antennas. Designing such tiny antennas raises several challenges due to the way body tissues are structured to absorb energy **(Gosalia et al., 2005; Soontornpipit et al., 2005)**. Consequently, designing an antenna that can integrate with IMD is crucial to verify the essential requirements of implantable antenna technology, such as small size, low power consumption, high-bandwidth, increased radiation efficiency with limited Specific Absorption Rate (SAR). As standard according to the *Federal Communications Commission* (FCC)**(Zheng et al., 2016; Soliman et al., 2021; Aliqab et al., 2023; Hu et al., 2023)**, the SAR value needs to be less than 1.6 W/kg and 2 W/10kg while 1g and 10 g tissues are taken respectively.

Antenna design for IMDs has been extensively studied in literature. The problem of large bandwidth and high-radiation efficiency of implantable antenna have been addressed in **(Kim et al., 2010)**. The recently published research papers have primarily concentrated on the design of implantable antennas within the Industrial, Scientific, and Medical (ISM) frequency band (2.4 - 2.48 GHz). To eliminate interferences with the surrounding devices, 402 MHz - 405 MHz has been selected by the Medical Implant Communication System (MICS) for such antenna types **(Asili et al., 2015; Emami-Nejad and Mir, 2017; Herth et al., 2017; Aleef et al., 2017)**. This clearly suggests that the wavelength, which is directly related to antenna size, should be about 74 cm. Therefore, reducing the size of implantable antennas presents a significant challenge for researchers. All the rules and regulations concerning frequency bands for implantable antenna can be found in **(Kiourti and Nikita, 2014; Malik et al., 2020)**.

Recent advancements in implantable antenna design focus primerly on enhancing efficiency, miniaturization, and biocompatibility for biomedical applications. The research conducted in **(Basir et al., 2023)** provides a comprehensive review of implantable and ingestible antennas, outlining their design processes, miniaturization techniques, and biocompatibility considerations while proposing a standardized protocol for development. The authors of **(Liska et al., 2024)** investigate the performance limitations of implantable antennas, employing convex optimization to analyze radiation efficiency and the trade-offs between tissue absorption and antenna losses. The work presented in **(Patil and Rufus, 2022)** explores the use of metamaterial substrates for performance enhancement, highlighting their potential in miniaturization and improving radiation characteristics. Moreover, a systematic review of implantable antenna designs, identifying key frequency bands, performance metrics, and challenges, is conducted in **(Mohan and Kumar, 2024)**. Lastly, the work by Arora et al. in **(Arora et al., 2020)** introduces a microstrip type antenna for Medical Implant Communications Service (MICS) applications, utilizing split-ring elements and a shorting pin to optimize impedance bandwidth and gain. In summary, these studies highlight the ongoing research efforts to enhance implantable antennas, addressing efficiency, design constraints, and biomedical compatibility.

Despite these advancements, several research gaps remain in the development of implantable antennas for IoT-based healthcare monitoring systems. Current studies mainly focus on single-band designs, particularly within the Industrial Scientific, and Medical (ISM) and Medical Implant Communication System (MICS) frequency bands **(Palandoken, 2017; Patil and Rufus, 2020)**. However, the development of multiband antennas, which could improve compatibility and mitigate interference, remains underexplored. Another critical challenge in implantable antenna design is ensuring a stable orientation (polarization) toward the intended receiver. This issue is especially challenging with linear polarization due to posture changes and human activities. Circularly polarized (CP) antennas offer a promising alternative as they maintain signal integrity despite variations in orientation. Therefore, the aims of this paper are twofold: (i) to review recent implantable antenna designs proposed for medical devices and (ii) to compare newly published studies with existing designs in the literature. This review focuses on two key properties of such antenna namely multiband-operations and circular polarization as they are the essential factors for improving performance in biomedical applications.

2. IMPLANTABLE ANTENNA DESIGNS

Implantable antennas are crucial elements of implantable medical devices (IMDs), maintaining effortless wireless connectivity for remote monitoring purposes. These antennas must be compact, biocompatible, energy-efficient, and highly reliable while operating within the human body. The selection of dual-band, circularly polarized, and multi-band antenna is driven by their ability to enhance efficiency, ensure stable communication, and adapt to various medical applications. Their superior performance (of implantable antennas) in dealing with essential challenges like signal integrity, power consumption, and interference reduction makes them the most effective choices for IMD applications.

2.1 Recent Dual-Band Implantable Antennas

This section presents an extensive literature review on dual-band implantable antenna designs suggested for healthcare purposes. Following medical implant communications system (MICS) specifications, this antenna is intended for operation in the ISM frequency range **(Karacolak et al., 2008; Quevedo-Teruel and Rajo-Iglesias, 2010; Duan et al., 2012; Liu et al., 2012; Xu et al., 2012; Kiourti et al., 2014; Xu et al., 2014; Liu et al., 2016; Alireza Akbarpour, 2017)**. Previously, glucose monitoring was conducted using biosensors that connected to a bulky and uncomfortable RF unit. In addition to the insufficient response time (3 to 5 minutes) of the biosensors, the short lifetime of the sensors and battery of the RF unit are the critical drawbacks of such system. To keep the overall size of the implant device small, designing a compact implantable antenna is highly required. A compact size, efficient, and comfortable antenna is introduced by **(Karacolak et al., 2008)** which can be used in implant devices for glucose-measurement applications. The antenna was configured for dual-band operation through the combination of finite element-boundary integral analysis and particle-based optimization. The designed implantable antenna operates in multi-band fashion, IMS (2.4 -2.48 GHz) and MICS (402-405 MHz). To evaluate the antenna performance in a realistic environment, gels imitating the special electrical characteristics of the human skin are introduced to perform in *vitro* tests. This testing is crucial because this type of antenna operates beneath the skin. Then, after testing the fabricated antenna in the designed gel environment, the results demonstrated a strong match between simulations and real-world data. The simulated bandwidths of the designed antenna are 4.2% ISM and 20.4% MICS, and the measured bandwidths are 7.1% ISM and 35.3% MICS. Besides, the antenna is designed in a very small size (22.5 mm x 22.5mm x 2.5mm) which makes it applicable for implant devices. One of the features of this antenna that contributes to a longer device lifetime is its ability to effectively switch between sleep and wake-up modes.

As previously mentioned, one of the challenges researchers face in designing IMDs is developing a compact antenna with high radiation efficiency. In addition, the designed antenna has to work in specific frequency ranges (MICS and ISM bands) to reduce the human body's influence on the antenna's dielectric properties. Antenna-size reduction is even more challenging when the antenna operates on MICS, this is due to the large wavelength of this band. In **(Quevedo-Teruel and Rajo-Iglesias, 2010)**, a multi-layer microstrip patch antenna that operates on both ISM and MICS bands is presented for IMDs. This is a multilayer-configuration antenna since the radiating components and the feeding line exist on separate levels. The radiating elements and spiral are interconnected and subsequently short-circuited to the ground to minimize the antenna size. The paper further studied how the human body affects the antenna's properties. Thus, imitation gels for the MICS and ISM bands were independently developed to incorporate the designed antenna. Then, simulated results were validated by measuring different variables including return loss, radiation efficiency, and radiation pattern. The primary accomplishment of the paper is size reduction, where the antenna's size was 1375.4 mm^3. Its radiation efficiency (40 percent for the ISM band and 23 percent for the MICS band) is similar to those reported in existing literature.

In **(Duan et al., 2012)**, the authors presented a dual-band antenna design with non-uniform excitation, suitable for IMD applications, such as neuro microsystem applications. For the antenna to be compatible with the application of neural recording, it is designed to have a small size (27 mm x 14 mm x1.27 mm) and operate in two frequency bands (433.9 MHz and 542.4 MHz). It is revealed that the measured and simulated bandwidths were quite comparable (7.3% and 7.9%). The proposed antenna has some unique properties such as easy connection with differential circuitries (this is because of differential configuration property), minimizing the noise caused by the matching circuits, cost-effectiveness, and easy fabrication. Therefore, such an antenna is more appropriate for IMDs, particularly neuro microsystems.

Dual-band planar inverted-F antenna and spiral microstrip antenna are introduced in **(Liu et al., 2012)** for medical applications. In addition to wider bandwidth and sufficient radiation efficiency, it is stated that the proposed antenna has a smaller dimension (16.5 x 16.5 x 2.54 mm^3) compared to the available designs in the literature. Similar antenna design is presented in **(Xu et al., 2012)** for telemetry applications. The difference between **(Liu et al., 2012)** and **(Xu et al., 2012)** is adding open slots at the ground plane of the antenna. Because of this modification sufficient improvement in terms of high bandwidth (i.e., this occurs due to the modification of the slot length) and low return loss (less than -10 dB) is obtained.

The paper of **(Kiourti et al., 2014)** proposes an implantable antenna for IMDs and an on-body antenna designed for use as on-body repeaters. The repeater is located close to the low-power IMDs to receive its weak signals and retransmit them to external devices, ending up with a larger range of IMD. IMDs can benefit from this on-body repeater by reducing power consumption and extending battery life.

Compact size and dual-band antenna which is suitable for implantable far-field wireless applications is developed in **(Xu et al., 2014)**. The spiral dipole is bent and then embedded on both surfaces of the substrate; this allows miniaturization of the designed antenna (67.8 mm^3). Further, an off-center feeding dipole is adopted, allowing dual-band operations (MICS and ISM bands). The antenna's sensitivity is different when planted in the human head than in one-layer skin. In all cases, the advised antenna has the ability to effectively work in both bands.

The authors in **(Liu et al., 2016)** presented a new differentially fed implantable dual-band antenna that is used for sensitive applications such as near-field biotelemetry. The proposed antenna does not need a balun and matching circuit to be merged into a differential RF front end. This is due to using shorting pin and meandered strip methods in the design.

The implantable electrically coupled dual-band loop antenna is proposed in **(Alireza Akbarpour, 2017)**. Lumped capacitor is the key method adapted to achieve miniaturization in the antenna size. It is also reported that the designed antenna has 5.9% and 1.2% bandwidths in MICS and ISM bands respectively. While its peak gains are -23 dB and -22.3

dB in these bands. In addition to the miniaturized size, the presented antenna has low SAR at both bands.

In the study of **(Faisal and Yoo, 2018)**, a biotelemetry instrument designed for scalp implantation has been recommended, presenting a highly miniaturized, low-profile implantable antenna with dual-band functionality in the ISM frequencies of 915 MHz and 2.45 GHz. With its compact dimensions of 9.8 mm^3 (7 mm × 7 mm × 0.2 mm), this antenna is the most miniaturized known to date. The antenna system reaches gain at its peak of -28.04 dBi and -28.94 dBi at 915 MHz, and -23.01 dBi and -23.06 dBi at 2.45 GHz, respectively. To validate the system, the antenna and its prototype were immersed in a 3D head phantom with saline solution, where the measured data closely reflected the simulations. The radiation pattern of the antenna system in the dominant E and H planes is omnidirectional and directed away from the human anatomical model, which meets the criteria for telemetry applications. Thus, the presented antenna system is suitable for scalp implantation, particularly for monitoring intracranial pressure. A comparison of the studied dual-band antennas can be found in **Table 1**. It is significant to mention that the dual-band antenna presented **(Faisal and Yoo, 2018)** offers more favorable properties, particularly considering its size, when compared to other antennas used in body area networks (BAN) for implantable applications.

Table 1. Comparison of the presented dual-band antennas.

Ref.	Antenna	Frequency (GHz)	BW (%)	Gian (dBi)	Antenna parameters
(Karacolak et al., 2008)	Meandere patch antenna	-0.402 -2.4	53.3 at MICS band 7.1 at ISM band	-9 at 2.4 GHz -34 at 402 MHz	Dimensions 1265.6 mm^3 Substrate-Rogers RO3210, h = 0.635mm, εr = 10.2, tan δ = 0.003.
(Quevedo-Teruel and Rajo-Iglesias, 2010)	Strip patch antenna	-2.4 -2.48	Very narrow BW	Not specified	Dimensions 1375.4 mm^3, Substrate-ARLON 1000, h= 1.27mm, ε_r = 10.2.
(Duan et al., 2012)	Differentiallyfed spiral antenna	-0.4339 -0.5424	7.3 at 433.9 MHz 5.4 at 542.4 MHz	Not specified	Dimensions 480.6 mm^3., Substrate-Rogers 6010, h = 0.635mm, ε_r = 10.2, tan δ = 0.0023
(Liu et al., 2012)	Planar inverted and Spiral microstrip patchantenna	- 0.43 -4.4	13 at MICS band 4.4 at ISM band	-30 at 402 MHz -31.5 at 430 MHz	Dimensions 691.5 mm^3., Substrate-Rogers 3010, h = 1.37mm, ε_r = 10.2, tan δ = 0.0023
(Xu et al., 2012)	π shaped antenna with two meanders strips	-0.43 -2.45	52.6 at 356 MHz -610 MHz 4.4 at 2.4 - 2.5 GHz	-28 at 402 MHz -27.7 at 433 MHz	Dimensions 468.1 mm^3, Substrate-Rogers 3010 h = 0.635mm, ε_r = 10.2, tan δ = 0.0035

(Kiourti et al., 2014)	Triangular-shaped patch antennas	-0.42 -2.4	20.2at 401 -457MHz at MICS 20. 1 at ISM	-31.7 at 402 MHz -27.2 at 2400 MHz	Antenna 1: Size: 399 mm^3, Substrate-Rogers RO 3210, h = 0.635mm ε_r = 10.2, tan δ = 0.003, Antenna 2: Size: 6720 mm^3 Substrate- FR4, h = 1.6mm ε_r = 4.4, tan δ = 0.002
(Xu et al., 2014)	Spiral dipole antenna	-0.42 -2.45	47.5 at MICS and 31.6 at ISM band	-30.5 at 402 MHz -19.2 at 2.45GHz	Size: 67.8 mm^3, Substrate-Roger 3010, h = 0.635mm. ε_r = 10.2, tan δ = 0.0035
(Liu et al., 2016)	Symmetric meandered strip antenna	-0.42 -2.4	7.4 at 389-419 MHz 6.6 at 2395- 2563 MHz	-36.7 at 402 MHz 27.1 at 2400 MHz	Size: 642.6 mm^3, Substrate-Roger 3010 h = 0.635mm, ε_r = 10.2, tan δ = 0.0023
(Alireza Akbarpour, 2017)	Electrically coupled loop antenna	-0.4 -2.45	5.9 at MICS band 1.2 at ISM band	-23 at MICS band -22 at ISM band	Size: 5x5x3 mm^3, Substrate-FR4 and RO4003, h = 1.6 mm and 0.5 mm ε_r= 4 and 3.37, tan δ = not specified
(Faisal and Yoo, 2018)	Hexagonal-shaped, four T-shaped slots embedded on the radiator	-0.928 -2.45	19.8 at 928 MHz 89.6 at 2.45 GHz	-28.74 at 951 MHz -25.65 at 2.45 GHz	10.08 mm^3.
(Ganeshwaran et al., 2019)	Circular patch of omnidirectional radiation pattern	-0.4 -2.4	38.1 at MICS 17.6 at ISM	-34.1 dB at (0.4 GHz) MICS -15.2 dB at (2.4GHz) ISM	797 mm^3, Rogers 6010 (εr = 10.2, tan δ = 0.0023), *h=2.54mm*

2.2 Recent Circular Polarized Implantable Antennas

Circular polarization is an important factor in minimizing the multipath effect as well as lowering bit error rates in wireless communications. Ideally, the polarization of the implantable antenna must be fixed toward the direction of the intended receiver. However, this is impossible in linear orientation due to posture movement and human activities **(Patil and Rufus, 2020)**. To tackle this problem, an antenna with circular polarization could be the most effective alternative solution. As CP antenna is not affected by the time-dependent alignment of the receiver and transmitter, it provides higher link stability, lower bit error rate, and lower multipath effect **(Xu et al., 2014; Li et al., 2016; Liu et al., 2016; Ke Zhang, 2017; Liu et al., 2018; Kaim et al., 2020)**.

An implantable antenna with a bandwidth improvement technique is presented in **(Xu et al., 2014)**. This optimized antenna can be used in capsule systems in ISM bands. In addition to the original resonance frequency, a new resonance frequency is achieved by integrating a strip to the dipole. Therefore, the antenna bandwidth is improved from 25.7% to 37.8%.

A broadband single-fed CP implantable antenna is proposed for medical applications in **(Li et al., 2016)**. The primary goal of that work is to design an implantable antenna that demonstrates improvements in both impedance bandwidth and axial ratio bandwidth. By

incorporating a specially shaped slot into the antenna's ground plane, both bandwidths are improved; however, the size of the slot must be selected with great precision. Moreover, this modification does not add any backward radiation, thereby; the patient's body will be prevented from harmful damage.
Authors **(Liu et al., 2016)** presented a compact single-fed large-beamwidth CP implantable antenna for a continuous glucose monitoring application. Antenna miniaturization (8.5 × 8.5 × 1.27 mm^3) is obtained with the help of a spit ring resonator (SRR) and four C-shaped slots.
In **(Ke Zhang et al., 2017)**, the design of an implantable CP antenna for biomedical applications band is considered. In this paper, a special miniaturization technique, by means of developing meandering slots and loading stubs, was adapted to make the designed antenna suitable for such applications. Further, by implementing this design procedure, a 65% reduction in size is achieved compared to the traditional loop antenna with perturbations.
An implantable CP antenna was introduced in **(Liu et al., 2018)** operates on 915 MHz and is used for the transmission of wireless power. To optimize the antenna for such applications, it requires a compact size and high radiation efficiency. To meet these requirements, stub-loading techniques along with capacitive coupling are used in the antenna design procedure. It is claimed that the designed antenna has the smallest volume as well as high radiation efficiency in contrast to the previously published CP antenna designs.
Researchers proposed an ultra-miniaturized CP coplanar waveguide (CPW)-fed implantable antenna in **(Kaim et al., 2020)** for biotelemetry applications. The author proposed an ultra-miniaturized CP patch antenna, called a ground radiation antenna, operating on a single band (2.4-2.5 GHz). The antenna has a circular shape, and circular polarization is achieved by loading its ground with two slots. Furthermore, the positions of the slots can be adjusted to easily obtain right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP). Through simulated and measured results, the presented antenna design is validated for biometry applications due to having a low profile and large bandwidth properties.
In **(Ahmad et al., 2022)**, a small-sized CP in-body antenna that operates in the ISM band at 2.45 GHz was introduced. The antenna is excited using a tapered CPW technique, and its radiator has a pentagonal design with five horizontal slots to produce circular polarization. A flexible Roger Duroid RT5880 substrate, characterized by a dielectric constant (εr) of 2.2, a loss tangent ($\tan\delta$) of 0.0009, and a thickness of 0.25 mm, serves as the base material. With dimensions of 21×13×0.25 mm^3, the antenna demonstrates a bandwidth ranging from 2.38 to 2.53 GHz (150 MHz) in a vacuum. Within skin tissue, the bandwidth ranges from 1.56 to 2.72 GHz (1.16 GHz), whereas in muscle tissue, it spans from 2.16 to 3.17 GHz (1.01 GHz), highlighting the variation in frequency response across different tissue types. **Table 2** compares the reviewed CP antennas.
Noticeably, due to having small size, high gain and high bandwidth, the circular polarized antenna proposed in **(Ahmad et al., 2022)** is a good candidate for ISM implantable devices.

2.3 Recent Multi-Band Circular Polarized Implantable Antennas

This section provides a systematic analysis of the latest published study on multi-band, circularly polarized implantable antennas.

Table 2. Comparison of the reviewed circular polarized antennas.

Ref.	Antenna	Frequency (GHz)	BW (%)	Gain (dBi)	Antenna parameters
(Xu et al., 2014)	Square Loop antenna	0.709 -0.975	29.4 from 709 MHzto 954 MHz, 27.8 from 737 MHz to 975 MHz	-37 dBi at 402 MHz	Size 214.6 mm^3. Substrate- Rogers 3010 h = 0.635mm ε_r = 10.2, tan δ = 0.0035
(Li et al., 2016)	Single fed patch antenna	-2.45	14 from 2.32 GHz to 2.67 GHz	−22.33 dBi at 2.45 GHz	Size 127 mm^3. Substrate- Rogers 3010 h: *no specifed*, ε_r = 10.2, tan δ = 0.003
(Liu et al., 2016)	square patch and C-shaped patch antenna	-2.45	13 from 2.31 GHz to 2.63 GHz	-17 dBi at ISM band	Size 91.75 mm^3. Substrate- Rogers 3210 h = 0.635, ε_r = 10.2, tan δ = 0.003
(Ke Zhang, 2017)	Square patch antenna	-0.915	10.6 from 865 MHz to 902 MHz	−27 dBic at 915MHz	Size 285.75 mm^3. Substrate- Rogers 3010 h = 0.635, ε_r = 10.2, tan δ = 0.0035
(Liu et al., 2018)	Square patch meandered antenna	-0.91	17 from 828 MHz to 982 MHz	-29dBic at 910 MHz	Size 153.67 mm^3. Substrate- Rogers 3010 h = 0.635, ε_r = 10.2, tan δ = not specified
(Kaim et al., 2020).	CPW patchantenna	-2.45	99.25 impende nce BWat IMS band.	-15 dBc at 2.45 GHz	Size: 85 mm^3. Substrate: RT Duroid 5880, h = 0.508mm, εr = 2.2, tan δ = 0.0009.
(Ahmad et al., 2022)	In-body patch antenna, with a CPW excitation.	-2.45	61.2 in vacuum, 47.2 in skin tissue and 41.2 in muscle tissue.	−2.7dB at 2.45 GHz	Size 21×13×0.25 = 68.25mm^3. Roger Duroid RT5880 material, εr = 2.2, *tanδ* = 0.0009 with *h= 0.25 mm.*

2.3.1 Miniaturized Triple-Band Circular-Polarized Implantable Patch Antenna for Bio-Telemetry Applications

In **(Kamel et al., 2022)**, a triple-band CP antenna was designed for integration with lossy tissue, aimed at bio-telemetry applications. The antenna operates within both the ISM bands (868–868.6 MHz and 2.4–2.4835 GHz) and the midfield frequency range (1.824–1.98 GHz). These frequency ranges support telemetry of physiological data, energy efficiency, and wireless power transmission in healthcare devices. A key advantage of this implantable antenna is its CP behavior across all three bands, distinguishing it from dual-band CP antennas reported in the literature. The antenna features a compact design with a total volume of 50.8 mm^3. Furthermore, SAR and link budget margin calculations were performed to ensure both health safety and reliable communication.

The design of the triple-band CP antenna is illustrated in **Fig. 1(a)–(c)**, with dimensions of 10 mm × 10 mm × 1.016 mm. **Fig. 1(a)** depicts the square-shaped radiator, **Fig. 1(b)** illustrates the ground plane featuring open-end slots, and **Fig. 1(c)** illustrates the antenna sideview. To lower the operating frequency and achieve circular polarization, the antenna includes a central annular ring with a pair of slits along its outer boundary, as well as two square corner slits etched in opposite directions on the square radiator. Moreover, the radiator is enclosed by three meander line slots to lengthen the current path, while the slotted ground structure contributes to bandwidth enhancement and frequency tuning. To achieve miniaturization, a via is strategically positioned at an optimal location, with a diameter of 0.4 mm, while a 50 Ω coaxial feed with a 0.28 mm diameter is used to excite the antenna. The substrate and cover layer are made from Rogers RO3010, a dielectric material with a dielectric constant (εr) of 10.2, a loss tangent (tan(δ)) of 0.0027, and a thickness of 0.508 mm. The cover layer prevents direct contact between the square radiator and the surrounding lossy tissue. The optimized parameters of the antenna were determined using Computer Simulation Technology (CST) software.

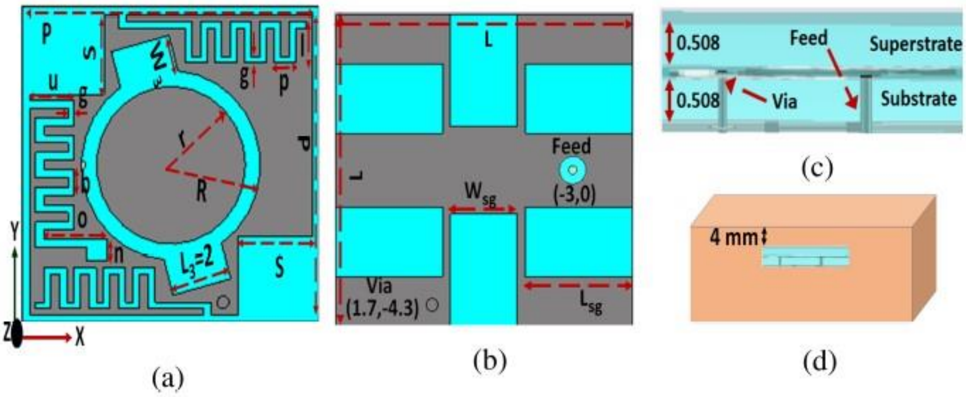

Figure 1. Designed antenna, (a) the antenna radiating surface, (b) antenna ground plane structure, (c) side view, and (d) simulation radiation box.

The |S11| of the fabricated antenna in saline solution and the chicken breast slab is calculated by connecting the coaxial cable to the Rohde and Schwarz ZVA67 vector network analyzer (VNA). The applied saline solution consists of 53% sugar and 47% deionized water. **Fig. 2(a)** illustrates the comparison between the measured and simulated |S11| of the designed antenna. The measured bandwidth (BW) of the impedance fabricated antenna in saline solution are 15.1% (0.86–0.99 GHz) and 25.5% (2.375–3 GHz) at the ISM bands, and 18.75% (1.66–1.975 GHz) at the midfield band. In the chicken breast tissue slab, the antenna shows impedance bandwidths of 26.6% (0.6375–0.837 GHz) and 6.8% (2.475–2.65 GHz) at the ISM bands, and 9.02% (1.58–1.73 GHz) at the midfield band. Small shifts between the measured and simulated reflection coefficients can be attributed to fabrication tolerances and connector soldering. For far-field testing, the fabricated antenna is placed in a 3-D box filled with saline solution inside an anechoic chamber as shown in **Fig. 2(b).** A comparison of the simulated and measured radiation patterns is presented in **Fig. 2(c),** showing good agreement at all three operating frequencies. Slight discrepancies were noted, probably due to the rotation of the manually constructed support structure that holds the 3-D box. The determined axial ratios (AR) of the antenna are 1.15, 0.54, and 2.408 dB at 860 MHz, 1.85 GHz, and 2.45 GHz, respectively.

The designed antenna provides effective impedance matching, higher gain than compared to the existing designs, and broad impedance and AR bandwidths. To verify experimentally, the designed antenna was fabricated using the photolithographic technic and tested in both saline solution and chicken tissue, mimicking the electrical properties of human tissue. Simulating the electrical properties of human tissue, there is a strong alignment between the measured and simulated results. Moreover, the SAR value was assessed and found to be within the acceptable limits set by IEEE standards, ensuring the safety of the patient.

2.3.2 Development of a Compact Dual Circularly Polarized Implantable Antenna Through the Characteristic Mode Technique

The paper by **(Song et al., 2024)** employs the characteristic mode technique to create a miniaturized dual-band CP implantable antenna to operate in ISM band. The compact design and dual-band properties are realized by using a slotting method and placing a short-circuit probe between the ground plane and the radiation patch. The characteristic mode method is used to analyze the current distribution of circular radiation patches with T-shaped slots across different modes.

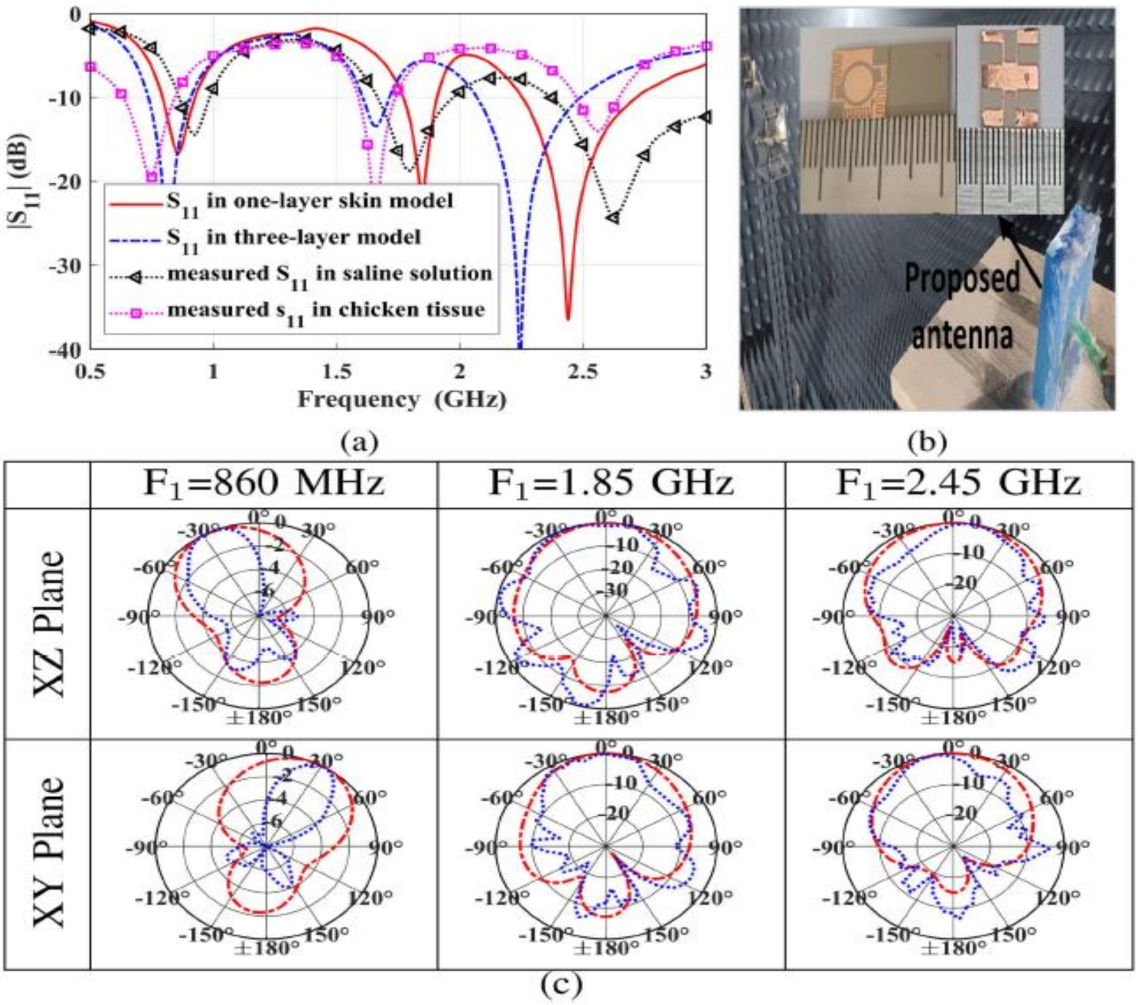

Figure 2. (a) Comparison of S-parameters between simulation and measurements, (b) far-field measurement setup within an anechoic chamber, and (c) comparison of simulated and measured radiation patterns of the designed antenna.

By introducing a cross-shaped slot at the center of both the radiation patch and the ground plane, two orthogonal modes with equal amplitude and a 90° phase difference are generated in the two operating frequency bands, ensuring CP characteristics. With total size of $\pi \times (0.014\ \lambda 0)^2 \times 0.0027\ \lambda 0$, the antenna is smaller than other CP implantable antennas with similar performance characteristics. Additionally, the suggested antenna offers appropriate gain and radiation efficiency.
The results demonstrate that the antenna operates in the ISM bands of 0.9 and 2.4 GHz, with effective 3 dB axial ratio bandwidths greater than 220 MHz (0.87 to 1.09 GHz, 22.45%) and 230 MHz (2.31 to 2.54 GHz, 9.48%). This design is also in accordance with IEEE safety standards.
The antenna's geometry is illustrated in **Fig. 3.** The antenna consists of a circular superstrate, a circular ground plane with a cross-shaped slot, a circular dielectric substrate, a coaxial feed, a circular radiation patch with four T-shaped and a cross-shaped slots. The superstrate serves as a protective layer, preventing the radiation patch from coming into direct contact with human tissue. The radiation patch is positioned on the upper surface of the dielectric substrate, while the ground plane is located on its lower surface. Rogers RT 6010 ($\varepsilon_r = 10.2$, $\tan\delta = 0.0023$) is utilized as the dielectric material, and slotting methods are employed to accomplish miniaturization. By introducing four T-shaped slots on the radiation patch, the impact of current path length is extended, resulting in a minimized antenna size.

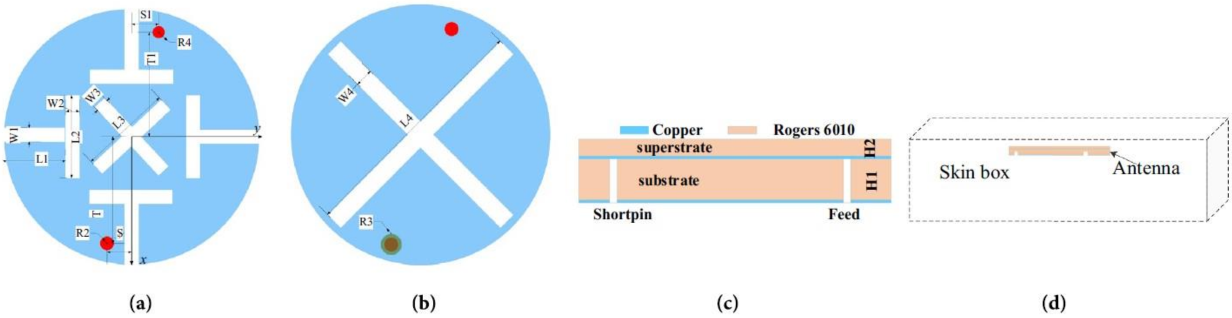

Figure 3. The antenna and its simulation setup are illustrated as follows: (a) Radiation patch featuring four open T-shaped slots and a cross-shaped slot, (b) Ground plane with a cross-shaped slot, (c) Side view of the antenna, and (d) Simulation environment.

The dual-band feature is achieved by placing a short-circuit element at the symmetric point of the feed port, connecting the radiation patch to the ground plane (GND).
The bandwidth can be further enhanced by appropriately adjusting the thickness of the dielectric substrate. Two cross-shaped slots of varying sizes are then introduced on the radiator and the ground plane to provide greater flexibility in tuning the antenna's operating frequency and 3 dB bandwidth of AR. This design effectively covers the 915 MHz and 2.45 GHz frequencies within the ISM band. The overall dimension of the antenna is $\pi \times (0.014\ \lambda_0)^2 \times 0.0027\ \lambda_0$.
Fig. 4 shows the measured and simulated S11 and AR. These two measures of S11 values align closely at 0.9 GHz. However, a minor difference is noted between the simulated results and the two measurements at 2.4 GHz. This is due to the fact that the electrical properties of the environment closely resemble, but are not identical to, those of the simulation environment. The antenna radiation pattern is illustrated in **Fig. 5**. The antenna's simulated and measured radiation patterns show a close agreement in both ISM bands. The minor discrepancy is due to differences between the simulated and actual test environments, as well as losses in the RF connection line.

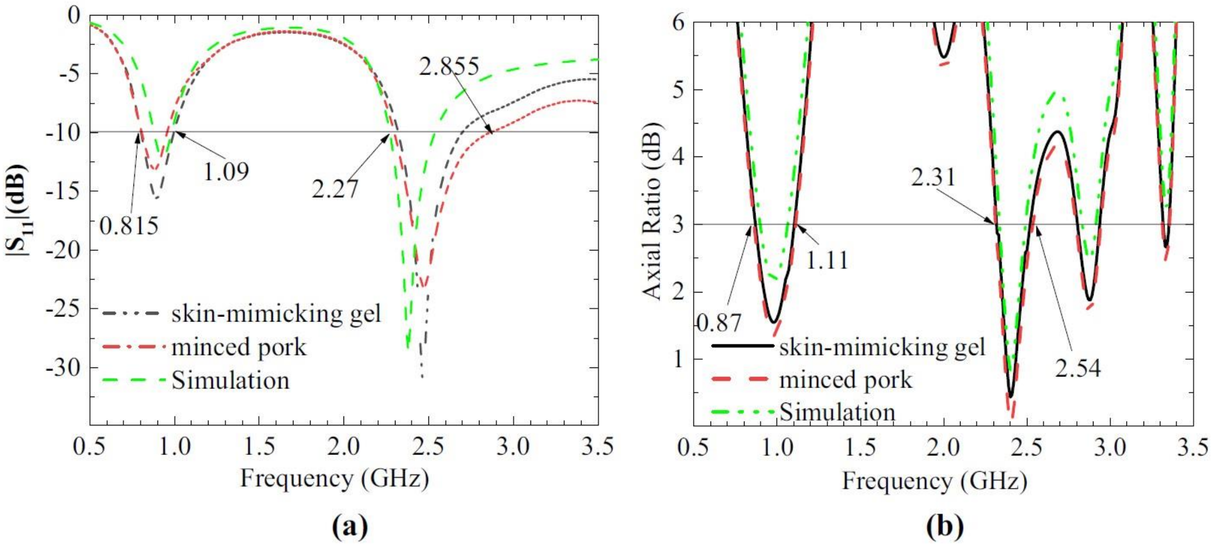

Figure 4. Comparative analysis of simulated and measured S11 and AR under different conditions. (a) S_{11}, (b) AR.

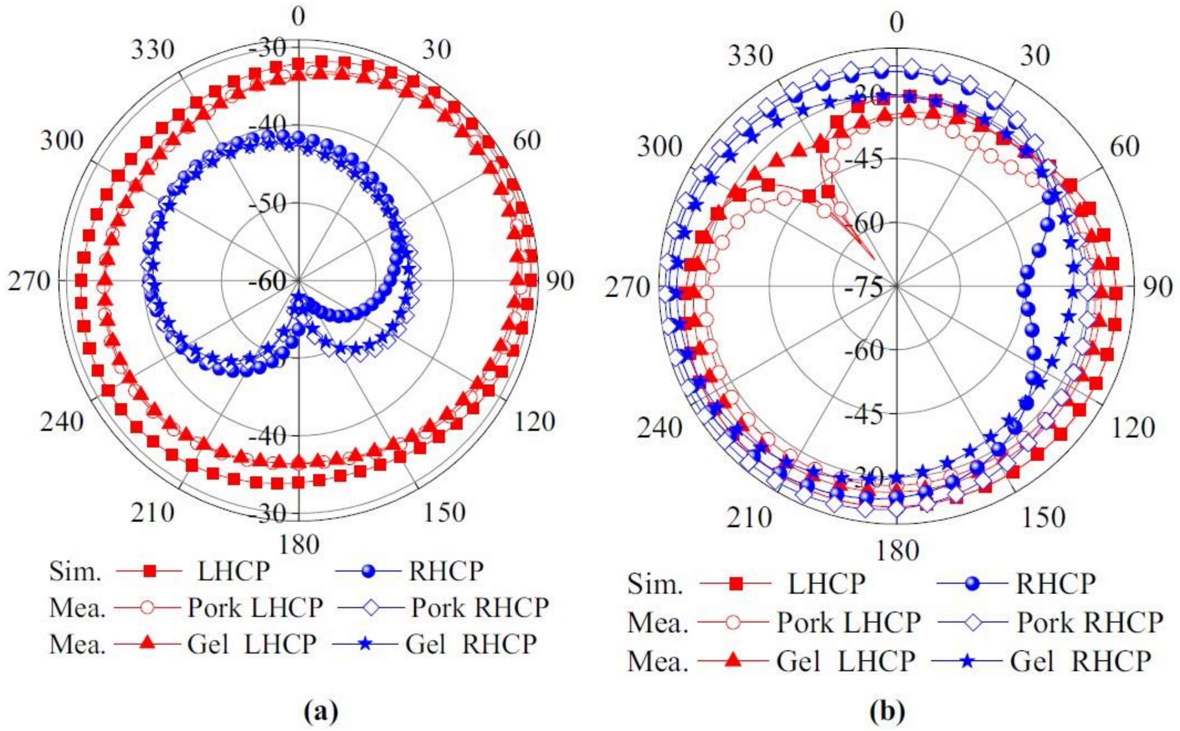

Figure 5. Measured and simulated and radiation patterns at phi=0°. (a) 0.9 GHz, (b)2.45 GHz.

In this study, the antenna prototype is fabricated and tested in skin gel and minced pork. The measurement results indicate that the effective 3 dB AR bandwidth ranges from 0.9 GHz to the 2.45 GHz ISM bands, with the radiation pattern showing excellent symmetry.

Its radius equals 0.0137λ0 (4.7 mm), where λ0 indicates the wavelength in accordance with the minimum free space operating-frequency. It is a promising candidate for use in implantable medical devices. Table 3 compares these two studies given in **(Kamel et al., 2022)** and **(Song et al., 2024)** with other works in literature .

Table 3. Comparison of these two studies given in **(Kamel et al., 2022**; **Song et al., 2024)** relative to existing literature

Ref.	Frequency (GHz)	BW (%)	Gain (dBi)	Size (mm^3)	CP
(Kamel et al., 2022)	0.86 1.85 2.450	15.6 7.5 18.7	-31.82 -21.8 -18.5	50.8	Yes - -
(Song et al., 2024)	0.915 2.45	24% 9.4%	-29.5 -19.2	58.56	Yes Yes
Valanarasi and) (**Dhanasekaran, 2020**	1.4 2.45	21.3 21.2	-32 -31.6	104.6	Yes -
(**Xu et al., 2020**)	1.4 2.45	21.3 -	-31 -32.6	103.7	Yes Yes
(Valanarasi and Dhanasekaran, 2020)	1.42 2.45	3.1 6.1	-25.7 -39.95	154.88	Yes Yes
(Bairappaka et al., 2022)	2.17 2.38 3.48	2.77 0.42 1.73	-23 - -	5619	Yes - -

3. DESIGNING IAS: KEY REQUIREMENTS AND DIFFICULTIES

Previous discussions have shown that IAs operate quite differently inside the human body compared to conventional antennas used in open environments. Nevertheless, the presented design criteria depend on the specific applications. This section outlines the main requirements and challenges related to these types of antenna.

3.1 Miniaturization

As they must fit within compact medical devices while maintaining efficient performance, miniaturization is a crucial design consideration for IAs. Advances in antenna fabrication technology have enabled the development of ultra-small IAs, such as those used in cochlear implants and retinal prostheses, which are inserted into the auditory nerves and eyeball. However, miniaturization remains challenging due to the constraints of traditional λ/2 or λ/4 antenna designs, particularly within frequency channels reserved for implanted devices, such as the Medical Device Radio Communication Service (MedRadio) (401–406 MHz), Industrial, Scientific, and Medical (ISM) bands (902–928 MHz and 2.4–2.45 GHz), and Medical Implant Communication Service (MICS) (402–405 MHz) **(Code, 1999; Kiourti et al., 2014; Chauhan et al., 2015)**. Effective antenna design must balance size reduction, signal integrity, and biocompatibility to ensure optimal functionality in biomedical applications.

3.2 Ensuring Patient Well-being

Due to the internal placement of such devices (i.e., IMDs), it is vital to take precautions to minimize the risk of tissue damage from electromagnetic exposure. To safeguard patient health, several precautions must be taken, as detailed below.

3.2.1 Specific Absorption Rate (SAR)

This criterion refers to the level of RF energy uptake by human tissues. It serves as a key measurement for assessing tissue response and safety during electromagnetic exposure. Globally, two standards regulate SAR levels. As per the IEEE C95.1-1999 standard, SAR must not greater than 1.6 W/kg when mean value taken over a 1-gram cubic volume of tissue **(Commission, 1999)**. The IEEE C95.1-2005 standard states that the SAR must not exceed 2 W/kg when averaged over a 10-gram cubic volume of tissue **(Lin, 2003)**. The FCC applies a 1-gram averaging method, whereas the ICNIRP recommends averaging over 10 grams **(Fields, 1997)**. A SAR of 2 W/kg over a 10-gram cubic volume of tissue is equivalent to approximately 4-6 W/kg when measured within a 1-gram cubic volume. To comply with standard SAR limits, implantable devices must operate within a limited power output. Typically, the Specific Absorption (SA) is calculated for each pulse based on **(Liu et al., 2016)**:

$$SA = T_P \times SAR \tag{1}$$

Here T_P represents the time span of the pulse. The absorption of electromagnetic power by body tissues might lead to an increase in temperature. To ensure safety, the tissue's internal temperature surrounding the implanted device must be less than 1-2°C.

3.2.2 Effective Isotropic Radiated Power (EIRP)

A high value of this type of power from an IA may pose possible harms to human health and interfere with the surrounding radio equipment. The official EIRP limit for an IA in the MedRadio and ISM bands is -16 dBm and -20 dBm, respectively **(Merli, 2011)**. To avoid tissue damage, the input power of an IA applied in data telemetry should be restricted. When the antenna functions in receiving mode, external power must be within the limits defined by current regulations.

3.3 Biological Compatibility

For IAs, this is a vital aspect in maintaining bodily safety. Contact between the antenna and body tissues may cause a short circuit, as the tissues possess electrical conductivity. Two principal approaches can be employed to achieve biocompatibility: One approach involves constructing the antenna from biocompatible materials, while the other entails encapsulating it with a biocompatible superstrate **(Soontornpipit et al., 2004)**. Some biocompatible materials employed in the development of this type of antennas include MACOR (ϵr = 6.1; tanδ = 0.005), Ceramic, and Alumina (ϵr = 9.4; tanδ = 0.006). Biocompatible encapsulation materials include PEEK (ϵr = 3.2; tanδ = 0.01) and Zirconia (ϵr = 29; tanδ ≈ 0) **(Skrivervik and Merli, 2011)**. Zirconia is considered an ideal choice for bio-encapsulation because of favorable electromagnetic features of this material. Thanks to its high permittivity and low loss tangent, it helps minimize power loss by focusing the antenna's near field within the encapsulation. On the other hand, Silastic MDX-4210 and PEEK offer the benefit of straightforward fabrication and ease of handling.

3.4 Techniques for Fabricating IAs

The manufacturing of IAs demands the utmost precision because of their designated function. A variety of advanced manufacturing techniques have been suggested in the literature, such as fabric-embroidered antennas, encompassing polymer composite encapsulation, microfluidic antennas, and 3D-printed antenna designs **(Nag et al., 2018; Mohamadzade et al., 2019)**. In **(Simorangkir et al., 2018)**, the conductive fabric was embedded in PDMS. Using this combination of conductive fabric and PDMS (serving as the substrate while also providing protective encapsulation) enables the creation of a more easily realized and durable flexible antenna structure compared to traditional fabrication methods.

4. CONCLUSIONS

The IA is the backbone of IMD and allows it to communicate with external devices.This paper has reviewed a variety of the proposed IA designs suggested for IMDs in IoT-based enabled health monitoring systems. The essential aim the current paper was on three IA types, dual-band, circular polarized, and multi-band circular polarized. A detailed literature survey of each of these antenna types has been conducted.

During the development process of IAs, human body attributes have to be considered since they may produce negative impacts on the antenna performance. Furthermore,IA does not operate in free space as conventional antennas do. Therefore, size optimization while preserving broad bandwidth capabilities, minimum power consumption, and high radiation efficiency with limited SAR brings another challenge for the researchers. To minimize power consumption of IMDs, multi-band operation is particularly important for IAs. Thus, the majority of the discussed antennas operate on both ISM (2.4 GHz - 2.48 GHz) and MICS (402 MHz - 405 MHz) bands.

The proposed antenna designs offer significant advancements and show great potential for implantable medical applications. However, further research is required to assess their effectiveness in both in vitro and in vivo environments, as well as to address biocompatibility concerns. Lastly, designing IAs involves distinct engineering challenges and requirements due to the inherent complexity of their operation within the human body. Key factors such as miniaturization, patient safety, and biocompatibility must be carefully balanced to ensure efficient performance and safety in medical applications. While advances in fabrication techniques and biocompatible materials resulted in the advancement of highly specialized antennas for applications like cochlear implants and retinal prostheses, there are still challenges related to SAR limits, EIRP, and antenna miniaturization. Ongoing research and innovation in antenna design, materials, and fabrication methods will continue to have a significant impact in improving the functionality and safety of implantable devices in the future.

NOMENCLATURE

Symbol	Description	Symbol	Description
AR	Axial ratio, dB	h	Substrate height, m
SAR	Specific Absorption Rate, W/kg	S_{11}	Reflection coefficient, dB
BW	Bandwidth, Hz	ε_r	Dielectric constant, dimensionless
T_p	Pulse duration, m/s	λ_0	Wavelength, m
tanδ	Loss tangent, dimensionless		

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Credit Authorship Contribution Statement

Zhwan M. Rashid: Conceptualized the review framework, defined the research scope, and conducted part of the literature survey with writing an initial draft of the manuscript.
Bakhtiar A. Karim: Conducted an extensive literature review, screened and selected relevant studies, synthesized key findings, and drafted the initial manuscript.
Asaad M.J Al-Hindawi: Contributed to critical discussions, provided in-depth analysis of the reviewed literature, refined the structure of the paper, and assisted in manuscript editing and formatting. All authors collaborated on interpreting the presented data and witting the manuscript. All of them also approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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الهوائيات الطبية القابلة للزرع لتطبيقات مراقبة الصحة القائمة على إنترنت الأشياء: مراجعة

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الخلاصة

في الآونة الأخيرة، اكتسبت الهوائيات القابلة للزرع الكثير من الاهتمام بسبب ميزاتها الفريدة ونطاقها الواسع من التطبيقات. أحد هذه التطبيقات هو التطبيق الطبي الحيوي حيث يجب أن يكون النظام المصمم قادرًا على العمل داخل أنسجة جسم الإنسان والتواصل مع جهاز خارجي. لتحقيق مثل هذا النموذج من الاتصال، بالإضافة إلى البرامج المتطورة، فإن تصميم الأجهزة المناسب أمر بالغ الأهمية. يجب أن يلبي الهوائي المصمم للتطبيقات الطبية الحيوية متطلبات مختلفة، مثل كفاءة الطاقة والحجم الصغير والعمليات متعددة النطاقات الترددية. لذلك، فإن تصميم الهوائي المناسب من حيث النطاق الترددي الكبير والاستقطاب الدائري والحجم الصغير للتطبيقات الطبية أمر بالغ الأهمية. الهدف من هذه الورقة هو إجراء مسح حول تصميمات الهوائيات الحالية التي أوصى بها الباحثون للأجهزة الطبية القابلة للزرع (IMDs). ستركز المراجعة بشكل خاص على ثلاثة أنواع من الهوائيات القابلة للزرع وهي الهوائيات ثنائية النطاق الترددي والاستقطاب الدائري والهوائيات ذات الاستقطاب الدائري متعددة النطاقات الترددية. ثم نقوم بتحليل نتائج أحدث المقالات المنشورة ومقارنتها بالأدبيات الموجودة. سيتم أيضًا مناقشة التحديات الأساسية أمام تصميم الهوائي القابل للزرع.

الكلمات المفتاحية: هوائي دائري الاستقطاب، هوائي ثنائي النطاق الترددي،IMD ، هوائي قابل للزرع.