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Microwave Antennas Suggested for Biomedical Implantation

Kasturi Sudam Patil and Elizabeth Rufus

Abstract

In the twenty-first century, there is an enormous development in various areas: microwave sensors have played an important role in medical devices, because of population growth and public awareness of the health of medical devices, they have become an ever-increasing technology. Microwave antenna sensors can be used to monitor human body temperature, implantable defibrillators, pacemakers, continuous glucose monitoring, heart failure detection, and so on. Antennas are also used as flexible sensors to monitor physiological parameters. Therefore, microwave sensors are used for wireless communication in various biomedical applications. The design of such antennas has gained considerable attention for dealing with issues such as miniaturization, biocompatibility, patient safety, improvement in communication quality, etc. The objective of this paper is to provide an overview of the requirements, design steps, and testing of a microwave antenna used in biomedical implantation. In this chapter, various antennas used in medical applications are described in detail. Also, antenna designing and testing requirements are discussed.

Keywords: implantable antennas, dual-band antennas, sensors, vivo test

1. Introduction

In latest years, microwave antennas have performed an important role in implantable biomedical devices. Millions of people around the world improved and saved their lives with the help of implants [1]. Implantable antennas play a role in creating a simulation environment, checking results, and fulfilling diagnostic purposes. With population growth and health awareness, people are more concerned about their health. Implantable medical devices (IMD) play an important role now a days. It is used to continuous monitoring of human body temperature [2], implantable cardioverter defibrillators and pacemakers [3], for continuous glucose monitoring [4], to detect heart failure [5], rectenna [6], and so on. In IMD an antenna is one of the essential parts. To design biocompatible antennas according to parameters, consider the required size, shape, miniaturization, impedance matching, biocompatibility, patient safety, and low power consumption [7, 8].

In the twenty-first century flexible electronics developing towards bio-integrated electronics for curvilinear biological skin, tissue, and organs considering patient's safety [9]. Diagnosis and treatment are application areas of antenna, diagnosis can be done with help of magnetic resonance imaging (MRI), biomedical telemetry, and wireless capsule endoscopy [10]. Integrated implantable antenna plays important role in bi-directional communication for controlling and monitoring external

equipment. The implantable antenna must be biocompatible, human tissues are conductive and it can be short circuit while coming into contact with metallization [11].

These are operated in very low frequencies such as medical implants communication system (MICS) band (402–405GHz) & Industrial, Scientific and Medical (ISM) bands (2.4–2.4835GHz) [12–23]. In 1999, Federal Communications Commission (FCC) decided the frequency range of Medical Implant Communications Service (MICS) operating on frequency range 402–405 MHz. It consists of a low-power, high-speed, non-voice transmission that is useful in the manufacture of implantable medical devices [24]. The design of an implantable antenna is challenging due to biocompatibility issues miniaturization, loss of transmission path in the human body, safety issues, and so on.

2. Different research areas for an antenna in biomedical application

Biomedical telemetry allows the measurement of physiological signals at some distance, these signals would be wired or wireless communication technologies. It helps to transmit and receive the data in a certain distance range. One of the developments in this field is an IMD. IMD consists of an antenna, electronic circuit, battery, and sensors. The antenna is built-in, it helps to transmit the signal from the human body to the exterior device. For this purpose following types of antennas are preferred.

2.1 Dual-band implantable antennas

The medical industry is continuously developing efficient and advanced systems that are suitable for the human body. In previous years, the ISM band was mainly used for antenna design [25], but the United States Federal Communications Commission (FCC) and the European Radio-communications Committee (ERC) allocated a frequency for biomedical telemetry [24, 26]. Communication between implants and the external unit is easy with the MICS band and ISM band used to send the awake signal to an external unit. MICS band is similarly intended for data communication, the ISM band is useful for startup signals.

To design dual-band, implantable antennas is a shift between sleep and wake-up mode for conserving energy and increasing the lifetime of antennas. The dual-mode operation generally improves the lifetime of the battery [27]. The advantage of a differentially fed dual-band implantable antenna can be connected easily with differential circuits, useful to help eliminate loss introduced by baluns and matching circuits [28, 29]. From the following **Table 1**, we can observe that Differential feed antenna is generally operated on two nearly frequencies/frequency bands such as 433.9 and 542.4 MHz [28, 34] and MICS (402–405 MHz) and ISM (2.4–2.48 GHz) [35, 36, 38]. Also dual-band antennas operated on two frequency bands such as MICS (402–405 MHz) and ISM (2.4–2.48 GHz) [27, 29, 33, 37, 40] 1.4 and 2.4GHz [39].

2.2 Circularly polarized antenna

Implantable antennas can communicate wirelessly with an external device. This is currently a great approach to stored physiological and real-time monitoring systems for biomedical telemetry [42]. Due to the effect of multipath distortion, communication with the help of far-field radio frequency (RF) link telemetry is sometimes affected. Since circularly polarized antenna preferred to the reduction of multipath and improvement of bit-error-rates can be achieved by circular

Ref.	Title and year of publication	Frequency bands	Antenna type	Antenna dimensions			Application	
				Dimension	Substrate	ϵ_r Thickness		
[27]	Characterization and testing of skin mimicking material for implantable antennas operating at ISM band (2.4–2.48GHz) (2008)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Dual band	22.5 × 22.5 × 2.5 mm	Rogers RO3210	10.2	0.635 mm	Glucose monitoring
[30]	Dual-band microstrip patch antenna based on the short-circuited ring and spiral resonators for implantable medical devices (2010)	MICS (402–405 MHz) And ISM (2.4–2.48 GHz).	Dual band micro strip patch antenna	1375.4 mm ³	ARLON1000	10.2	1.27 mm	Medical application
[28]	Differentially fed dual-band implantable antenna for biomedical applications (2012)	433.9and 542.4 MHz	Differential feed dual band antenna	27 × 14 × 1.27 mm	Rogers 6010	10.2	0.635 mm	Neural signal recording
[29]	Compact dual-band antenna for implantable devices (2012)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Dual band antenna	16.5 × 16.5 × 2.54 mm	Rogers3010	10.2	1.37 mm	Medical application
[31]	Dual-band implantable antenna with open-end slots on ground (2013)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Dual band antenna	19 × 19.4 × 1.27 mm	Rogers3010	10.2	1.27 mm	Biomedical telemetry application
[32]	A broadband implantable and a dual-band on-body repeater antenna: design and transmission performance (2014)	Medradio 401–406 MHz & ISM (2.4–2.48GHz)	Dual band I. Broad band implantable antenna II. Dual-Band On-Body Repeater Antenna	I. 3.99mm ³ II. 6720mm ³	I. Roger RO 3210 II. FR4	I. 10.2 II. 4.4	I. 0.635 mm II. 1.6 mm	The human trunk

Ref.	Title and year of publication	Frequency bands	Antenna type	Antenna dimensions				Application
				Dimension	Substrate	ϵ_r	Thickness	
[33]	Miniaturized dual-band implantable antenna for wireless biotelemetry (2014)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Dual band antenna	$10.2 \times 10.2 \times 0.675$ mm	Rogers3010	10.2	0.635 mm	Biomedical applications especially human head or human arm implantable wireless communication
[34]	Design and in vitro test of a differentially fed dual-band implantable antenna operating at MICS and ISM bands (2014)	433.9 and 542.4 MHz	Differential feed dual band antenna	$13.4 \times 16 \times 0.835$ mm	Rogers RO 3210	10.2	0.635 mm	Wireless medical telemetry services
[35]	A novel differentially fed compact dual-band implantable antenna for biotelemetry application (2015)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Differential feed dual band antenna	$22 \times 23 \times 1.27$ mm	Roger 3010	10.2	0.635 mm	Near field biotelemetry
[36]	Miniaturized differentially fed dual-band implantable antenna: design, realization, and in vitro test (2015)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Differential feed dual band antenna	$27 \times 9 \times 1.27$ mm	Roger 3010	10.2	0.635 mm	Biomedical application
[37]	Miniaturized dual-band implantable antenna for wireless biotelemetry (2016)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Dual band	$8.75 \times 7.2 \times 0.5$ mm	Rogers 6010	10.2	0.25 mm	Wireless telemetry
[38]	Differentially fed compact dual-band implantable antenna for biotelemetry (2016)	MICS (402–405 MHz) and ISM (2.4–2.48 GHz).	Differential feed dual band antenna	$22 \times 23 \times 1.27$ mm	Roger3010	10.2	0.635 mm	Biotelemetry
[39]	Dual-band implantable antenna with circular polarization property for ingestible capsule application (2017)	1.4 and 2.4GHz	Dual band		Rogers 3010	10.2	0.635 mm	Ingestible capsule application

Ref.	Title and year of publication	Frequency bands	Antenna type	Antenna dimensions			Application	
				Dimension	Substrate	ϵ_r		Thickness
[40]	Dual-band electrically coupled loop antenna for implant applications (2017)	(2.4 and 4.8 GHz).	Dual band		I. FR4 II. RO4003	I. 4 II. 3.37	I. 1.6 mm II. 0.5 mm	Implant application
[41]	Dual-band (2.4–4.8 GHz) implantable antenna for biomedical telemetry applications	(2.4 and 4.8 GHz).	Dual-band	12 × 12 mm	Rogers3010	10.2	0.635 mm	Biotelemetry application

Table 1.
Dual-band and differential fed implantable antennas.

polarization [43]. The design of the circular polarized (CP) antenna is difficult and needs to be miniaturized. Here, good circular polarization is achieved with a limited size [44]. Circular polarization has a special advantage in that it becomes insensitive between transmitter and receiver [45].

An Implantable patch antenna was first described with capacitive loading in [43], its axial ratio bandwidth is below 3 dB is narrow about 1.63%. [43]. In a circularly polarized helical antenna, measured impedance is 40% and axial radial bandwidth is 32.6% [46]. Similarly, in a loop antenna, simulated impedance and axial ratio bandwidth is 18.2%. [44]. Broadband CP implantable antenna exhibits its axial ratio bandwidth is 6.09% and wide impedance is 16.05% [45]. A miniaturized complementary split ring resonator (CSRR) was designed 915 MHz and its axial ratio bandwidth was 2.4% and impedance bandwidth is 12.2% [47]. Recent research on the CP ISM band antenna contained axial ratio -18.2% and impedance bandwidth 6.2% [48]. Recent work of CP ISM band at 915GHz consists axial ratio bandwidth and impedance band with 1.2 and -29% respectively [49]. **Table 2** shows all recent information about the circularly polarized antenna.

2.3 Capsule antennas

Capsule endoscopy is a diagnostic technology for gastrointestinal (GI) imaging that complements conventional endoscopy. An ingestible electronic radio telemetry capsule, first developed in 1957, is used to measure pressure and temperature [50]. It consists of the ability to transmit detailed information in real-time like growing heatstroke among the athletes while transmitting information to the receiver it simultaneously monitoring body temperature [51]. The approximate size of the capsule is 11×26 mm, in this small size it consists CMOS imager, light-emitting diode, transmitter, batteries, antennas, detailed track of the digestive system. Also, for prevention conditions such as gastroparesis and iron deficiency anemia [52, 53].

Wireless telemetry is used for real-time diagnostics, which is easy for disease diagnosis. The capsule orientation is random, but a robust continuous communication link for biomedical telemetry is quite a challenge to develop stable and secure communication links for capsule devices. The antennas are designed and must be characterized electromagnetically [54, 55]. **Figure 1** shows in detail information about a biomedical capsule. It has eight different parts such as optical dome, lens holder, short focal length lens, light-emitting diode, CMOS Imager, batteries, radio telemetry transmitter, and antenna.

Various antenna designs for capsule antennas have been designed and developed in the literature, including multilayer spiral, multilayer helical, dipole, and complementary split resonator antennas. Antenna performance can be done with help of matching, radiation patterns, link budget, and characterization of wireless medical telemetry characterization. Wireless medical telemetry services (WMTS), industrial scientific and medical (ISM) band used for performance evaluation [56]. **Table 3** shows design techniques, operating frequency, the radiation performance of capsule antenna.

In [57] capsule is off-centered, the antenna operates in MedRadio 403 MHz and ISM 2.45 MHz bands and gain is for 403 MHz, [58] capsule is off-centered and distance to a surface is 10 mm. The bandwidth almost covers 403Mhz, ISM 434,868, 915, and 2.45GHz bands. The gain is about 434 MHz [61]. In [62] capsule is off-centered and the distance to a surface is 3 mm. The motivation is to improve the transmission range of a miniature in a body, but there are some difficulties such as poor radiation efficiency, strong coupling to biological tissues with loss and scattering, antenna impedance detuning, etc. Capsule antenna also considered for animal biotelemetry, electromagnetic properties of some animal tissue differ from humans. High robustness can reduce impedance detuning [63].

Ref.	Title and year of publication	Frequency of operation	Depth	Antenna dimensions				Gain [dBi]	Axial ratio BW
				Dimension	Substrate	ϵ_r	Thickness		
[43]	Capacitively loaded circularly polarized implantable patch antenna for ISM band biomedical applications (2014)	2.4GHz	4 mm skin	$10 \times 10 \times 1.27$ mm	Rogers 3010	10.2	0.635 mm	-22	~1.63%
[46]	Circularly polarized helical antenna for ISM-band ingestible capsule endoscope systems (2014)	2.4GHz	50 mm muscle	$\Pi \times 5.5^2$ mm \times 3.81	Rogers 3010	10.2	0.635 mm	-32	~32.6%
[44]	Miniaturized circularly polarized loop antenna for biomedical applications (2015)	2.4GHz	2 mm skin	$13 \times 13 \times 1.27$ mm	Rogers 3010	10.2	0.635 mm	-14	~2.4%
[45]	Broadband circularly polarized implantable antenna for biomedical application (2016)	2.4GHz	5 mm muscle	$10 \times 10 \times 1.27$ mm	Rogers 3010	10.2	0.635 mm	-22.33	~6.09
[47]	A miniaturized CSRR loaded wide-beam width circularly polarized implantable antenna for subcutaneous real-time glucose monitoring (2017)	915 MHz	4 mm skin	$8.5 \times 8.5 \times 1.27$ mm	Rogers 3010	10.2	0.635 mm	-27	~1.5%
[48]	Miniaturized circularly polarized implantable antenna for ISM-band biomedical devices (2017)	915 MHz	3 mm skin	$15 \times 15 \times 1.27$ mm	Rogers 3010	10.2	0.635 mm	-32	~18.2%
[49]	Circularly polarized implantable antenna for 915 MHz ISM-band far-field wireless power transmission (2018)	915 MHz	4 mm skin	$11 \times 11 \times 1.27$ mm	Rogers 3010	10.2	0.635 mm	-29	~1.2%

Table 2.
Circular polarized antennas for biomedical applications.

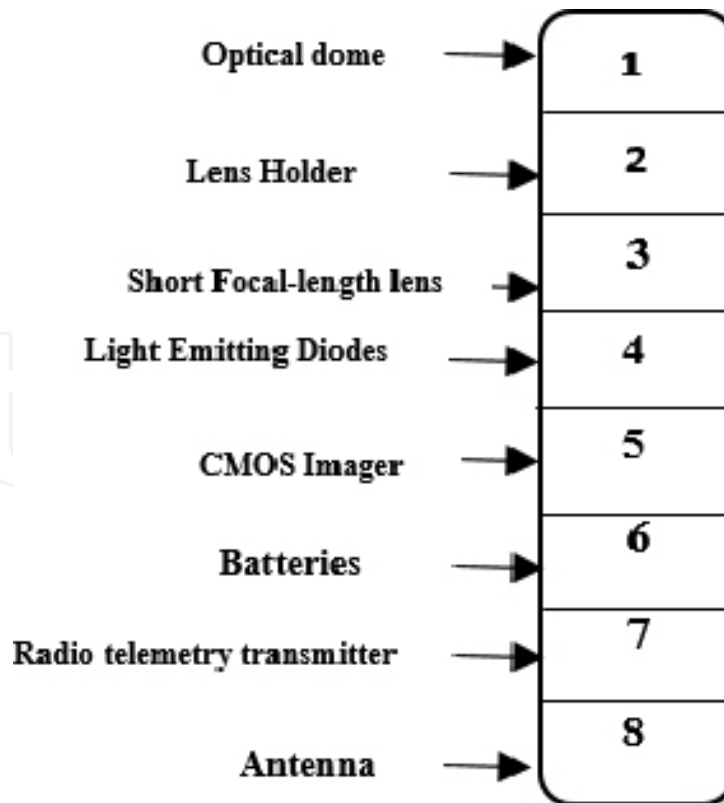


Figure 1.
Detail digestive track of a biomedical capsule.

3. Implantable antenna design requirements of an antenna

The implantable antenna design expects a small antenna size, broadband, low profile, and efficient antennas that can be used for data transmission, health monitoring, etc. The effective design depends on miniaturization, bandwidth, tuning, biocompatibility, patient safety, etc.

3.1 Miniaturization

In the case of an implantable antenna, an antenna supposes to be implanted in the human body, therefore the size must be should be minimized. Miniaturization becomes very important today because dimensions of half-wavelength ($\lambda/2$) and quarter wavelength ($\lambda/4$) antennas at low-frequency bands, ISM, MICS band makes them useless for designing implantable antennas. Generally, for the implantable antenna design MICS (402–405 MHz), ISM (Industrial, Scientific, and Medical 2.4–2.48 GHz) and Med Radio (401–406 MHz) bands are useful. While design, human tissue is designed with high relative permittivity, due to this antenna miniaturization being challenging. When a biocompatible layer with low permittivity is inserted around the antenna, the effective permittivity decreases. Various miniaturization methods are shown below.

3.1.1 High permittivity dielectric substrate

One of the techniques for reducing the size of the implantable antenna is to use a high dielectric constant substrate. In general, due to the high permittivity, the effective wavelength is shortened and the resonance frequency changes to a lower

Ref.	Title and year of publication	Antenna type	Size of capsule	G [dBi]	Approach towards miniaturization	Frequency of operation (MHz)	Phantom Details in (mm)		
							Size	Shape	Tissue
[55]	Conformal ingestible capsule antenna: A novel chandelier meandered design (2009)	Multilayer Spiral	26 × Ø11	-26	Meanders	1400	200 × 350 × 350	Box	Muscle
[57]	Design, realization and measurements of a miniature antenna for implantable wireless communication systems (2011)	Multilayer helical	32 × Ø10	-29	Stacking: four layers	Dual-band	110 × Ø80	Cylinder	Muscle
[58]	New flexible medical compact antenna: design and analysis (2012)	Microstrip	17 × Ø7	-33	Meanders, shorting, $\lambda/4$ SIR	434	Ø200	Cylinder	$\epsilon_r = 49.6$, $\sigma = 0.51$
[59]	a novel conformal antenna for ingestible capsule endoscopy in the medradio band (2013)	Microstrip	24 × Ø10	-30	Meanders, shorting	402	100 ³	Cube	Muscle
[60]	Circularly polarized helical antenna for ISM-band ingestible capsule endoscope systems (2014)	Loop w/ CSRR	26 × Ø11	-32	Stacking: three layers	2450	100 ³	Cube	Muscle
[61]	A broadband flexible implantable loop antenna with complementary splitting resonators (2015)	Assym. Dipole	25 × Ø10	-25	—	Multiband	Ø180 × Ø100 × 50	Elliptical cylinder	Muscle
[62]	Bandwidth enhancement of an implantable antenna (2015)	Assym. Dipole	24 × Ø11	-37	Meanders	402	180 ³	Cube	Skin
[63]	Robust ultraminiature capsule antenna for ingestible and implantable applications (2017)	Microstrip	17 × Ø7	-22	Dielectric loading, $\lambda/2$ SIR	434	Ø100	Sphere	Muscle
[64]	<i>In vivo</i> characterization of a wireless telemetry module for a capsule endoscopy system utilizing a conformal antenna design antenna (2018)	Multilayer helical	30 × Ø10	-23	Meanders	433	190 × 190 × 190	cube	Muscle

Table 3.
Capsule antennas: Literature.

Material	Dielectric constant	Ref.
Rogers RO3210	10.2	[27, 32, 34]
ARLON 1000	10.2	[30]
Roger 6010	10.2	[28, 37]
Rogers 3010	10.2	[29, 31, 33, 35, 36, 38, 39, 41, 43–48]
FR4	4.6	[32, 40]
RO4003	3.7	[40]
RT/Duroid 6002	2.94	[54]
MACOR	6.1	[7]
Alumina	9.4	[65]
RT/Duroid 6010	10.2	[66, 67]
Rogers TMM13i	12.2	[68]

Table 4.
List of materials used for implantable antenna design.

frequency. **Table 4** shows in detail a list of materials used for the design of the implantable antenna. For reducing the size of the implantable antenna, one can use a high permittivity substrate.

Generally, Roger 3010/Roger RO 3210/Rogers6010/ RT/Duroid6010, ARLON1000, Alumina, MACOR, FR4, RO4003, etc. substrate materials utilized for the design of the implantable antenna. The relative permittivity of Roger 3010/Roger RO 3210/Rogers6010/RT/Duroid6010 is 10.2 shown in the table. In [68] miniaturization achieved by high permittivity substrate material used i.e., Rogers TMM13i. ($\epsilon_r = 12.2$).

3.1.2 To improve impedance matching

The loading technique is used to improve impedance matching. In [29] the shorting strip is used as an inductive loading and compensates for the capacitive effect on the structure. Inductive loading capacitive loading plays an important part in this method, it is used to offset the imaginary part of the impedance. Therefore, a good impedance match is obtained at the desired frequency [42]. In [44], miniaturization was achieved by loading four patches and high impedance lines to form slow wave propagation, 54.4% miniaturization was achieved. In [61] antenna impedance matching was obtained with help of CSRR, which introduces negative permittivity (capacitance) and reduces the large inductive part of the loop antenna. Hence, less reflection and large radiation occur. In [69, 70] inductive loading techniques are used for miniaturized antenna size. Capacitive loading technique used in [71], antenna size reduced about 72% with help of circularly polarized microstrip patch antenna at the frequency of interest (fixed operating frequency).

3.1.3 Lengthening of the current flow path of radiator

Gain reduction can be possible by keeping a high relative dielectric constant of materials and planar inverted F antenna (PIFA) type antenna with structures like meandered, spiral, slot, etc. The longer the path of the radiator, the resonant frequency can be shifted towards a lower resonant frequency. Hence, size can be reduced. In [47] the antenna is square shape (case a), on which the current path is

short and the resulting resonant frequency is 4.5GHz. As considering lower resonant frequency, to increase the effective length of the current path four C-shaped slots surrounding the patch edges (case b). CSRR is one of the MTM (Metamaterial) structures, it offers negative permeability values. So, the electrical length of this MTM unit cell is smaller than the wavelength at operating frequency (case3). A circular CSRR is loaded in the center of the patch and resonant frequency shift occurs at 2.45GHz. In [55] meandered dipole structure gives vector current alignment which helps miniaturization.

3.1.4 High frequency

As we know, a higher operating frequency will result in a shorter wavelength. Hence, an antenna that can be designed at a higher frequency will result in, small volume. In literature implantable antennas works in frequency bands like MedRadio 401–406 MHz [32, 72], MICS (Medical implants communication Service) 402–405 MHz [7, 27, 29–31, 33, 35, 36, 54, 65, 70, 71, 73–80] and ISM (Industrial, Scientific and Medical) 2400–2480 MHz [32, 33]. In literature, it's reported that the MICS band is more preferably used for the design of the implantable antenna. In [56] an implantable antenna and capsule antenna were designed at wireless telemetry services (WMTS) band 1395–1400 MHz for performance evaluation and it is used for remote monitoring of patient's health.

3.1.5 Adding shorting pin

Shorting point is another method to miniaturize the size. In this technique, a shorting pin is inserted in between the patch plane and ground plane which increases the effective size of the antenna and reduces physical dimensions. In literature reported as [6, 7, 27, 29, 31, 54, 66, 73–77, 81] etc. consists shorting pin. Which helps miniaturize the size of the antenna. In [63] half-wave stepped impedance resonator (SiR) technique with two impedance steps, low-to-high and high-to-low to reduce the size of the antenna. In [67] antenna is miniaturized by adding two kinds of rectangular slots onto the annular ring.

3.2 Patient safely

Due to the propagation of electromagnetic field causes rise in temperature in human tissue, to evaluate this heat issue SAR is used. Generally, issues related to patient safety limit maximum allowable power incident on the implantable antenna. The rate of energy deposited per unit mass of tissue is called a Specific Absorption Rate (SAR). SAR is an internationally accepted FCC (Federal Communication Commission) guideline. For example, IEEE C95.1-1999 patient safety standard restricts the specific average of over 1 g of tissue in the shape of a cube to less than 1.6 W/kg ($(SAR_{1g, \max} \leq 1.6 \text{ W/kg})$), IEEE C95.1-1999 is found to restrict transmission power up to 5.186 mW [82] and ANSI/IEEE C95.1-2005 standard restricts the Specific Absorption Rate averaged over any 10 g of tissue in the shape of cube less than 2 W/kg ($(SAR_{10g, \max} \leq 2 \text{ W/kg})$), IEEE C95.1-2005 is found to restrict transmission power up to 30.17 mW [83]. To attenuate electromagnetic interference, MedRadio regulations restrict effective radiated power of implantable antenna to 25 μ W [84], power transmission is restricted to 50 mW. In [61] CSRR reduces the electric far-field of antenna this power absorption and SAR also reduced. As a result, radiation power increases, antenna radiation, and gain are increased.

SAR can be defined with the following equation,

$$SAR = \frac{\sigma|E|^2}{2\rho} \quad (1)$$

where, ρ (Kg/m^3) is mass density, σ (S/m) is conductivity and $|E|$ is electric field intensity.

3.3 Biocompatibility

Biocompatibility is one of the necessary conditions while designing an implantable antenna to preserve patients' safety. Human tissues are conductive, if they were allowed direct contact with metallization then there is a chance of short circuit. For long-term implantation, it's crucial to handle biocompatibility and prevention from short circuits. Most of the materials from **Table 4** are not biocompatible materials. There are different biocompatible materials reported in literature like macor [7], alumina [65], PDMS, Parylene C film, polyimide, PEEK (polyetheretherketone), polyethylene, silastic MDX4-4210 [46], etc. For thickness of encased biocompatible coating material can also affect the antenna performance [85].

3.4 Wireless communication ability

In the current scenario, an implantable antenna acts as a transmitting device, and an external device acts as receiving device as shown in **Figure 2**. Assuming far-field communication, the link power budget can be described as in terms of [43, 86, 87],

$$\text{Link Margin (dB)} = \text{Link} \frac{C}{N_0} - \text{Required} \frac{C}{N_0} \quad (2)$$

$$\text{Link Margin (dB)} = P_t + G_t - L_f + G_r - N_0 - \frac{E_b}{N_0} - 10 \log 10 B_r + G_c - G_d \quad (3)$$

Where P_t is transmitted power, G_t is transmitted antenna gain, L_f is path loss in free space, G_r gain of receiving antenna, and N_0 is the noise power density. Also, Path loss can be given as,

$$L_f(\text{dB}) = 20 \log \left(\frac{4\pi d}{\lambda} \right) \quad (4)$$

Where d is the distance between transmitter and receiver.

Impedance Mismatch loss is given as,

$$L_{imp}(\text{dB}) = -10 \log (1 - |\Gamma|^2) \quad (5)$$

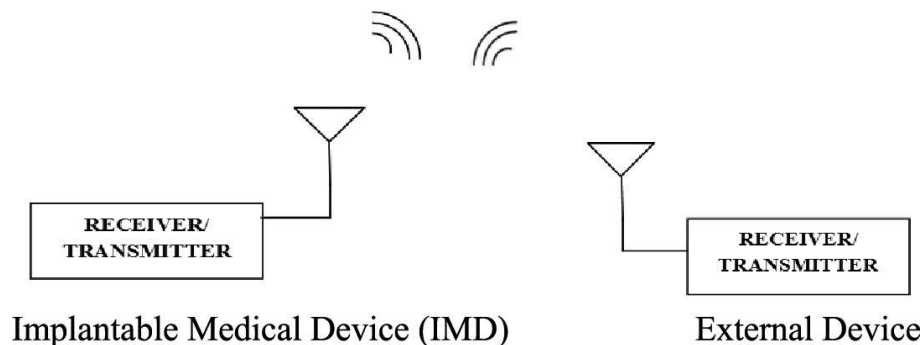


Figure 2. Wireless communication link between IMD and external device.

Where Γ is the reflection coefficient.

For, wireless communication, Link C/N₀ must exceed than required C/N₀, in uplink transmission input power of the transmitter antenna is limited for safety purposes. Received power can be given as,

$$p_r = p_t + G_t + G_r - L_f - L_{imp} - e_p \quad (6)$$

Where e_p is polarization mismatch loss between transmitter and receiver.

4. Antenna design and testing

4.1 Antenna design

While designing an antenna one should follow the following characterization of implantable antenna:

- Consider, operating frequency bands: MICS (402–405 MHz), ISM (2.4–2.48GHz), MedRadio (401–406 MHz) according to application.
- Design a low-profile antenna that fulfills conditions (tissue properties, dielectric constant, conductivity, etc.) of the human body.
- Evaluation of simplified geometry for a designed implantable antenna in the human torso.
- Further, evaluation and testing of the designed antenna in terms of radiation efficiency, return loss and bandwidth, etc.
- Formation of links between transmitter and receiver antennas, estimate the performance of communication links used in an implantable antenna, fulfillment of SAR limitations, and maximum Effective radiating power.
- **Table 5** shows volume occupied by an implantable antenna in the literature.

Following commercial tools are used for designing an implantable antenna such as computer simulation tool (CST) Microwave Studio, High-Frequency Structure Simulator (HFSS), Advanced Design System (ADS), and XFDTD. In [55] for analyzing electromagnetic characteristics of the implantable antenna inside head and body, Finite-difference-time-domain (FDTD) and Spherical dyadic Green's function (DGF), etc. functions are applied. In [83] Antenna simulated using FDTD overall efficiency improved and suitable design obtained in minimal time with help of a genetic algorithm.

In general, a one-layer skin model is widely used for implantable antenna design. Although, 2/3 muscle model and three-layer tissue (skin, fat, muscle) model are also typically for antenna designing. These three models make simulation efficient and measurement easier as this model is made from different materials to active accurate permittivity and conductivity.

In [26] implantable antenna designed with FDTD method including 2/3 muscle model. In [28, 33] antenna simulated in HFSS and CST respectively and a single-layer skin model is used. To design an implantable antenna in a realistic environment then it must evaluate within accurate human body models such as the human Voxel model shown in **Figure 3**. For neural recording systems and wireless

Ref.	Simulation tissue	Band (MHz)	Miniaturization technique					Vol. (mm ³)	
			Dielectric material	Substrate shape	Dielectric constant	Patch shape	Shorting pin		Patch stacking
[73]	Skin	402–405	Rogers 3210	Rectangular	10.2	Spiral	—	—	10,240
[54]	2/3 muscle	402–405	RT/duroid 6002	Rectangular	2.94	Waffle	Yes	—	6480
[73]	Skin	402–405	Rogers 3210	Rectangular	10.2	Spiral	Yes	—	6144
[7]	2/3 muscle	402–405	MACOR	Spiral	6.1	Spiral	Yes	—	3457.4
[30]	Skin	402–405	ARLON1000	Square	6.1	Meandered	Yes	—	1375.4
[27]	Skin	402–405 2400–2480	Rogers 3210	Rectangular	10.2	Meandered	Yes	—	1265.6
[74]	Skin	402–405	Rogers 3210	Rectangular	10.2	Spiral	Yes	—	1200
[75]	Skin	402–405	Rogers 3210	Rectangular	10.2	Meandered	Yes	—	1200
[66]	2/3 muscle	402–405	RT/duroid6010	Rectangular	10.2	Spiral	Yes	—	823
[81]	Muscle	402–405	Rogers 3210	Rectangular	10.2	<i>I</i> -shaped	Yes	—	791
[31]	Skin	402–405 2400–2480	Rogers3010	Rectangular	10.2	<i>I</i> -shaped with two meandered strip	Yes	—	487.8
[76]	Skin	402–405	Rogers 3210	Circular	10.2	Hook-slotted	Yes	Yes	335.8
[77]	Vitreous humor	402–405	Rogers 3210	Square	10.2	Spiral	Yes	Yes	273.6
[6]	Skin	402–405 433–435 2400–2480	Rogers 3210	Square	10.2	Comb and <i>I</i> -shaped	Yes	Yes	254
[78]	Skin	402–405	Rogers 3210	Circular	10.2	Meandered	Yes	Yes	203.6

Ref.	Simulation tissue	Band (MHz)	Miniaturization technique						Vol. (mm ³)
			Dielectric material	Substrate shape	Dielectric constant	Patch shape	Shorting pin	Patch stacking	
[79]	Human chest muscle	401–406	Rogers 3010	Square	10.2	1. square patch; 2. square patch with a central square slot 3. meandered square ring 4. meandered square ring with shorting pin	Yes	Yes	198.4
[71]	Skin	402–405	Rogers 3210	Square	10.2	Spiral	Yes	Yes	190
[70]	Skin	402–405	Rogers 3210	Circular	10.2	Hook slotted	Yes	Yes	149.2
[65]	Skin	402–405	Rogers 3210	Square	10.2	Hook slotted	Yes	Yes	121.6
[67]	Skin	2400–2480	Roger3010	Circular	10.2	Two rectangle slots onto the annular ring	—	—	120.69
[33]	Skin	402–405 2400–2480	Rogers 3210	Rectangular	10.2	Spiral dipole	—	—	67.8
[80]	Skin	402–405	Alumina	Circular	9.4	Meandered	Yes	Yes	32.7
[37]	Human head model	402–405 2400–2480	Rogers 3210	Rectangular	10.2	Serpentine	—	—	31.5
[72]	Skin	401–406	Rogers RT/duroid 6010,	Rectangular	10.2	I shaded reactive loading	—	—	18.1

Table 5.
 Volume occupied by MICS, ISM and medradio band implantable antenna and its miniaturized techniques: A literature.

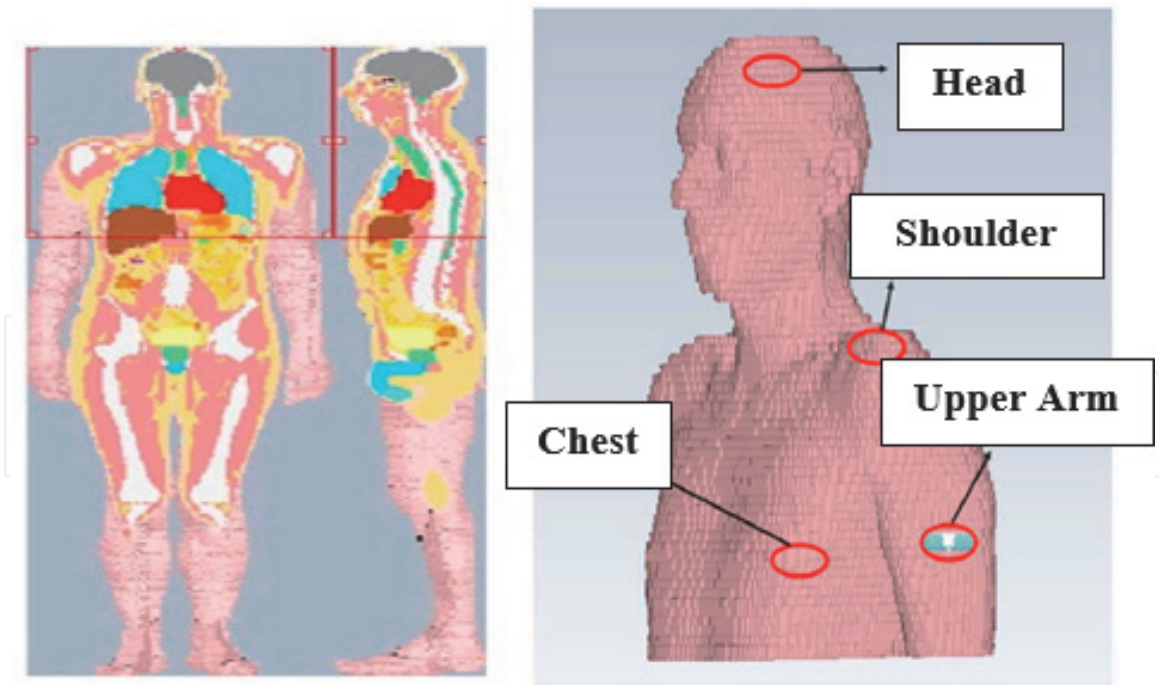


Figure 3.
Front and side view of CST human voxel mode used for simulation testing of various antenna.

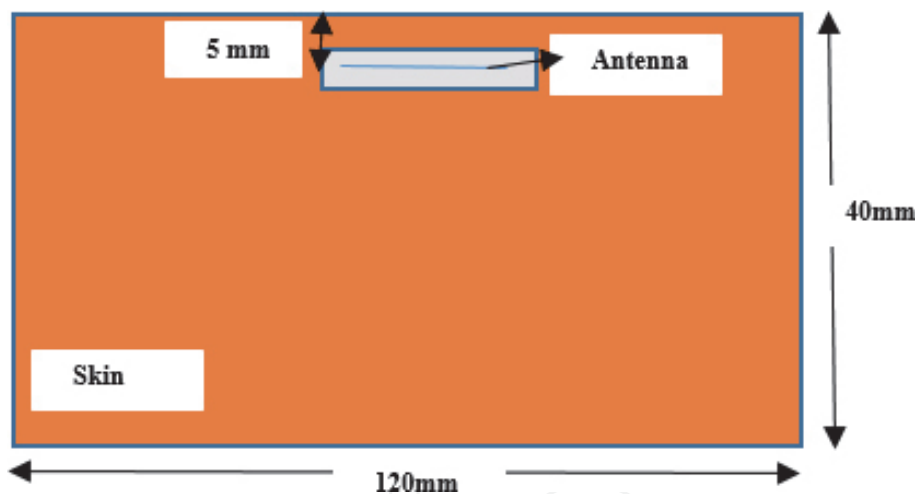


Figure 4.
One layer tissue model.

endoscope systems, an accurate human model is required. For different biomedical applications, the implant's position and depth could be a different and single layer or three-layer modeling used according to application. In **Figure 4** one-layer tissue model is shown.

5. Testing

5.1 In-vitro test

The meaning of In-Vitro is an outside living organism, this test is relatively easy and practically implementable because testing exists inside the phantom. Phantom is a container (cube or box) with liquid or gel material, it consists of the electrical properties of biological tissue. Fabricated prototype inserted in tissue phantom and measured. Phantoms are generally prepared with the help of deionized water,

sugar, salt, etc. If sugar concentration is increased, the permittivity of tissue significantly decreases and conductivity slightly increases and if salt concentration increased, it results in permittivity of tissue decreases and conductivity significantly increases. The mixture must be properly heated and stirred to avoid air bubble formation and poured inside the phantom. In [88] Measurement of liquids electrical properties (ϵ_r and μ) was conducted with a dielectric probe kit or open-ended coaxial cable. Generally, reflection coefficient, path loss, communication link, and polarization factor, etc. measured in vitro test, as observed in the literature. Generally, prototype antennas are connected with a network analyzer through a coaxial cable, inserted in a tissue phantom, and measured.

5.2 In-vivo test

In-vivo test, testing performed inside animal tissue. There are two methods for Vivo testing, embedding an implantable antenna inside donor animals and surgically implanting an antenna inside a live animal. In [64, 89] dual bands MICS (402–405 MHz) and ISM (2.4–2.48GHz) tested in vivo. A vivo testing protocol must be developed before the experimental investigation. Pre-surgical preparation, anesthesia, etc. should be needed. In [89], two antennas were implanted in three different rats. Due to surgical procedure variation, affect exhibited on return loss frequency response. Dielectric properties of live tissue generally depend on frequency, age, temperature, sex, etc. parameters. In [90–93] in vivo testing was performed to explore the effect of live tissues on antenna performance. In [91] biocompatible capsule device was implanted inside a live pig body for temperature monitoring. Two circular polarized antennas were tested in rat muscle in [93].

6. Conclusion

In this paper, microwave antennas for biomedical applications are presented. A brief overview of different antenna types and the needs of the implantable antenna is given. The design of an implantable antenna mainly depends on miniaturization, biocompatibility, wireless communication ability, and patient safety. Different types of antenna, frequency bands for the design of the implantable antenna, miniaturization techniques, etc. were studied. Implantable medical devices now a day are used for physical monitoring, diagnosis purposes. Many other factors will come into the picture when these antennas are integrated with any biomedical device. Low battery power is one of the main constraints. While designing an implantable antenna, dimensions of antenna, patient safety, lower power consumption, efficiency, battery lifetime, etc. should be considered.

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Author details

Kasturi Sudam Patil and Elizabeth Rufus*
VIT University, Vellore, Tamil Nadu, India

*Address all correspondence to: elizabethrufus@vit.ac.in

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