A BRIEF REVIEW ON IMPLANTABLE ANTENNAS FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

With the launch of cardiac pacemakers in 1960s, implantable medical devices are becoming more desirable for health services. As the devices designed to monitor physiological data inside the human body already have prove to provide major contributions to disease prevention, diagnosis and therapy as minimally invasive devices reduces hospitalization terms, thus improving the patients' quality of life. Biomedical telecommunication permits the transfer of information from on body to off body or from on body to on body or from in body to off body . Implantable antennas in medical devices are one of the highest priority devices particularly in receiving attention for scientific interest in integrating these implanted devices and radio frequency enabled telemetry. The design of these implanted devices has been in considerable attention in regarding to the developments of various parameters like biocompatibility, miniaturisation of size, patient safety, improved quality of communication with exterior and interior control equipment, insensitivity of tuning along with various mathematical method and optimisation techniques .The focus of my review paper is to provide an overview of these challenges and to discuss some of the ways in which these are dealt.

***Keywords*: *biocompatibility, human tissues, phantoms, implants, biodurability*.**

SECTION I

I.INTRODUCTION

In recent years flexible and portable electronics have received attention due to their wide variety of applications and applicability. They are particularly interested in bio-medical applications, in which they now are being widely used. Implants or implantable antennas is one area where wide applications are currently being done. According to a market analysis these flexible electronics have a market estimates of US dollar 30 billion by 2017 and over 300 billion USD by 2028 [1].Among the components of implants, BCWC plays a very important role, because here antennas come into the picture and antenna plays the crucial link between the implanted device inside the body and the receiver outside or on the body[2]. This design is crucial because of the various physiological limitations provide by the human body and The regulations of radiation involved for implanted devices. Inductive link and radio-frequency (RF)ink are the two kinds of link for biomedical communications. Inductive links have long been the most prevalent method for the biomedical telemetry for implanted medical devices[3][4],but they suffer from low data rates(1-30 kbps), restricted range of communication(<10 cm) and increased sensitivity to inter coil positioning, So the current trend in most implantable devices is towards radio frequency(RF) linked devices. Millions of people in the world are currently

ISBN: 978-93-86171-36-8

depended on various implanted RF linked devices for various bio medical applications ,including temperature monitors[5], pacemakers and cardioverter defibrillators[6], functional electrical stimulators[7], blood glucose sensors[8]. As technology is evolving, new implantable devices are now being developed and their usage is expected to rapidly increase exponentially. However current research is oriented towards RF-linked implantable medical devices. Patch antennas are currently receiving considerable attention for implantable antennas, because they are highly flexible in design, shape and conformability, thus allowing for relatively easy miniaturisation and integration into the shape of the implanted medical device.

The ITU-R recommendation SA.1346[9] outlined the use of the 402-405MHz frequency band for medical implant communication systems(MICS).This spectrum of 3MHz allows for 10 channels(a bandwidth of 300KHz each) in order to support simultaneous operation of multiple implantable medical devices in the same area and to limit interference from the co-located meteorological aids service band(401-406 MHz). The 433.1-434.8 MHz,868-868.6 MHz,902.8-928 MHz and (2400-2500 MHz) ISM band are also used for implantable medical biotelemetry in some other countries[10]. As human bodies are lossy and consists of different tissues of different values of permittivity and conductivity and these values again differ from one tissue to another tissue requiring different considerations, for each tissue, hence different implantable antennas are designed for different sites of implantations in the human body .thus design of implantable patch antennas has attracted high scientific interest for fulfilling the requirements of bio-compatibility, miniaturization, patient safety, frequency band of operation and high-quality communication with exterior equipment along with numerical and experimental methods. An overview of the design parameters ,mode of design and limitation are presented.

This paper is organised in four sections ,the first section deals with the design issues and limitations faced in designing, the second section presents the mode of design being used in the implantable sector. The third section deals with the recent technologies in implantable devices and the fourth section deals with the lapses of implantable technology.

SECTION II

I. DESIGN CONSIDERATIONS

Bio-compatibility and Bio-durability

The very important criteria in implantable antennas is that it should biologically adhere well to the human body in order to preserve safety and prevent rejection of the implant. As we know that human bodies are partly conductive, it would short the implanted antennas if it once comes in direct contact with the metallisation.the most common method to ensure biocompatibility and separation of metal radiator from biological tissue is to encased the antenna in a superstrate material.

Researchers have proposed a flexible slot antenna operating in ISM band. To make their design bio compatible for implantation, it is embedded into PDMS(Poly Dimethyl Siloxane)[11].

It is then tested by immersing it in a human phantom liquid, mimicking the dielectric and electrical properties of the human muscle tissue a study of the sensitivity of the antenna performance as a function of the dielectric parameters was performed[11]. The design issues addressed by this model are:

1.Evaluation of the characteristics of the antenna in terms of reflection coefficient in planar and bent state, E-field and gain[11].

2.Study of the sensitivity of the liquid mimicking the human muscle tissue, varying its nominal dielectric values[11].

3.Checking the SAR limitations, by means of SAR measurements[11].

Further measurements shows that the s_{11} parameters in planar and bent state in the ISM band demonstrate a very large bandwidth in both states, fully covering the ISM band. The s_{11} shows at -23.8dBi gain at theta(θ)= -46^0 and phi(ϕ)=90^0.Also the measured SAR values with an input power of 2Mw averaged in 1-g and 10-g tissue shows that the antenna respects the ICNIRP and FCC guidlines for general public exposure[11].this is shown in fig.2[11].

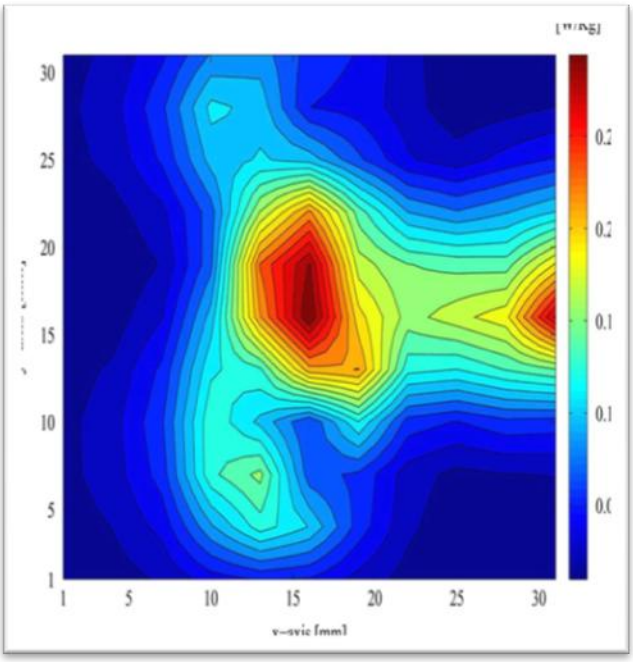


Fig. 1:SAR distribution for an input power of 2Mw [11]

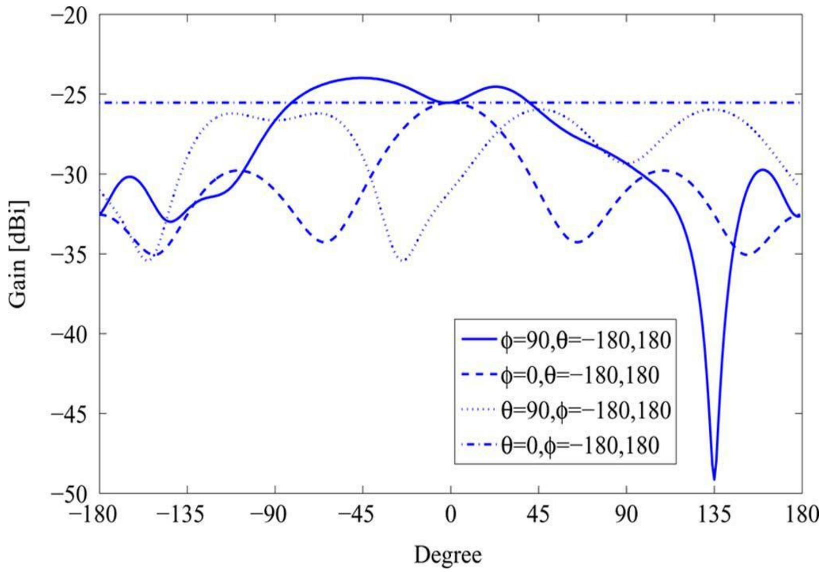


Fig. 2: return loss variation with angles at 2.45GHz[11]

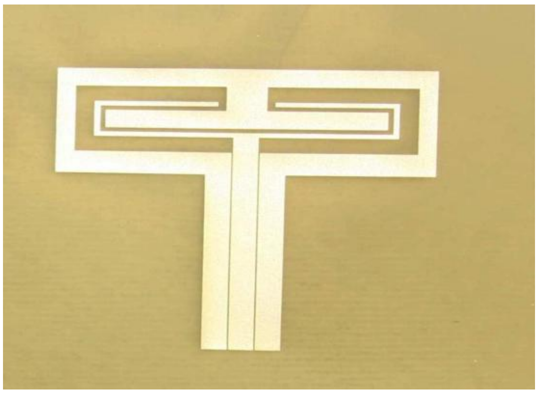


Fig. 3:Top view of the flex antenna without PDMS[11]

Fig. 4:Side view of antenna and cable embedded in PDMS[11]

Another widely used method is to simply prevent the direct contact with the metallisation of the antenna with the human tissue, to ensure biocompatibility of the human body with the antenna substrate. Here commonly used materials include
Teflon(€r=2.1,tanδ=.001),Ceramic alumina (€r=6.1,tan δ=.006)[12].An insulating antenna with a thin layer of low loss biocompatible coating is also another reported approach as shown below in the figure 5[12]

(a) (b)

Fig.5: a)silicone b)antenna encased in silicon[44]

Some other materials used for superstrate are Zirconia(€r=29,tanδ=0),Biomedical grade based Elastomer(€r=3.3,tanδ=0),PEEK(€r=3.2,tanδ=0.01) [12]

II. MINIATURISATION

Due to advances in the implanted biomedical devices technology the need for an ultra small designs for implanted devices is very much needed as traditional antennas of half wavelength (λ/2) and quarter wavelength (λ/4) are deemed unfit to be used as implanted biomedical devices due to their size and volume complications.

2.1 Use of PIFA antenna

PIFA is actually a patch antenna where a shorting pin is introduced.An implantable compact planar inverted antenna designed for wireless telemetry is being proposed operating in Australian ISM band of 900 MHz and

ISBN: 978-93-86171-36-8

915-928 MHz. This antenna has been tested inside the body of a live rat.The dimensions are (12×12×4)mm cube[13]. The PIFA antenna is basically developed from the monopole antenna. Inverted L is realised by folding down the monopole in order to decrease the height of the antenna at the same time maintaining identical resonating length. When feed is applied to the inverted L, the antenna appears as inverted F. The thin top wire of inverted F is replaced by planar element to get the planar inverted F antenna. Also the addition of a shorting pin between the ground plane and patch planes increases the effective size of the antenna, thus further reducing the physical dimensions[14].

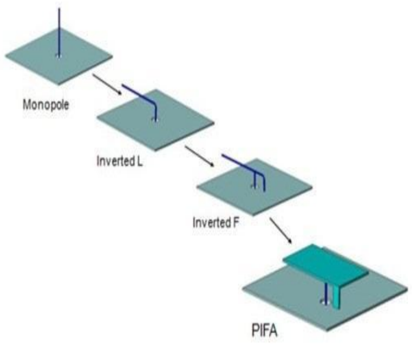


Fig. 6:PIFA from monopole[14]

The predicted bandwidth was found to be 8.5% less at 10dB return loss. The sensitivity of antenna impedence matching to variations in the rats body material in investigated. The antenna works well in the ISM band, even when body tissues parameters change within a significant range. The antenna model was designed using the CST software[13].

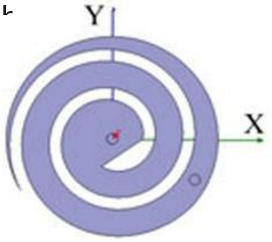
2.2: Use of high permittivity materials

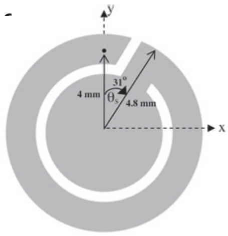
The use of high permittivity materials dielectrics are also done for miniaturisation of implanted antennas, e.g:Rogers 3210[15], Ceramic alumina[16] ,because they shorten the wavelength and result in lower resonance frequencies, thus assisting in antenna miniaturisation. Even the use of such high superstrate materials is not good enough because the superstrate layer still insulates the antenna from the higher permiitivity tissue[17]. Dielectric materials with high permittvity values and thin superstrate layers are thus solicited.

2.3: Lengthening the current flow path

Another means for miniaturisation is shown by using longer effective current flow paths excited on the radiation patch can also further reduce the resonance frequency. So non conventional shapes like hook[18],spiral[19] and patch staking methods by [15],[20] are also used as shown in fig 2

a. b.





c.

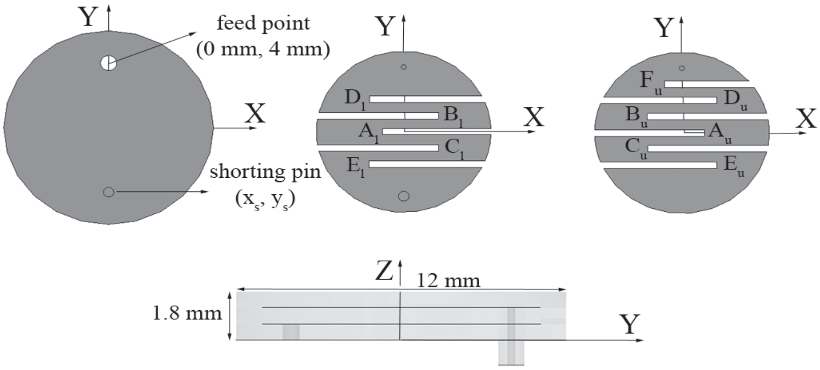


Fig.7: Lengthening of the current-flow path on the patch surface: (a) hook slotted [18] (b) spiral [19] (c) patch stacked PIFA antenna[20]

III. HEALTH HAZARDS AND SAFETY TO HUMAN BODIES

Issues related to patient safety limit the maximum allowable power incident on the implantable antenna. The Specific Absorption Rate (SAR) (the rate of energy deposited per unit mass of tissue) is generally accepted as the most appropriate dosimetric measure, and compliance with international guidelines is assessed. For example, the IEEE C95.1-1999 standard restricts the SAR averaged over any 1 g of tissue in the shape of a cube to less than 1.6 W/kg ($SAR_{1g,max}$ = 1.6 W/kg)[21].ICNIRP basic restrictions limit the SAR averaged over 10 g of contiguous tissue to less than 2 W/kg [22].For reducing the spatially averaged SAR in human tissue. Replacing the uniform-width spiral radiator of an implantable MICS PIFA with a nonuniform-width radiator was found to decrease the electric-field intensity and, in turn, the $SAR_{1g,max}$. The simulated near-electric-field distribution showed that the high electric-field area of the PIFA employing the nonuniform-width radiator was much smaller than that of the original PIFA . The value of $SAR_{1g,max}$ was thus reduced from 310 W/kg to 210 W/kg, considering a net input power of 1 W[23].

IV. FIELD GAIN

As medical implant communication systems (MICS) comprises of the implantable medical device and an exterior monitoring/control device, which is placed at some distance (typically, 2 m) away from the body [24]. Implantable antenna should thus provide a signal that is strong enough to be picked up by the exterior device, regardless of any power limitations. It is important to highlight that apart from patient safety, interference issues also limit the maximum allowable power incident on the implantable antenna so a defined limit of -16 dBm(25 μW) has been set on the effective radiated power (ERP) of implantable medical devices[24].

V. POWER CONSUMPTION

If operated continuously, the implantable medical device's transceiver will consume significant energy, and reduce the lifetime of the implantable medical device. There exist some methods for recharging the battery (e.g., via an inductive-loop approach. However, using the biotelemetry link only when necessary would be highly advantageous. For this purpose, a transceiver with dual-band operation may be used, such as the commercially available Zarlink ZL70101 transceiver [25]. The system uses two frequency bands, one for "wake-up" and one for transmission. The transceiver stays in "sleep mode" with low power consumption(1 μW) until a "wake-up" signal is sensed in the 2450 MHz ISM band. In the normal mode, the implantable medical device is fully powered, and exchanges data in the MICS band. Following the data transfer, the implantable medical device's transceiver returns back to the "sleep mode" again[26].

VI. HIGHER OPERATING FREQUENCY:

For medical implants various bands are approved. They are Medical Device Radio Communication Service (Med Radio, (401-406 MHz)[27] , and Industrial, Scientific, and Medical (ISM, 433-434.8 MHz , 902-928 MHz,2.4-2.5 GHz and (5.725-5.875 GHz) [28]. The formerly known MICS band (402-405 MHz) is mostly used for medical implant communications. An impulse radio ultra-wideband (IR-UWB) pulse operating at a center frequency of 4 GHz and a bandwidth of 1 GHz was chosen in as the excitation to the implantable antenna[29]. The capsule antenna and implantable antenna were designed at wireless medical telemetry services (WMTS) band (1395-1400 MHz)[30-31].Higher operating frequency will have shorter wavelength thus the antenna at higher frequency can be designed with small volume. As higher operating frequency with possible wide bandwidth is more suitable for high data-rate communication. However, higher operating frequency will cause large biological tissue loss in human body and path loss in free space .So factors such as device dimensions, operating frequency and transmission distance should be always within the overall framework of device parameters.

VII. MODELLING OF HUMAN TISSUES

In numerical simulations, implantable antennas are analyzed inside inhomogeneous lossy media that simulate biological tissues. Biological tissues have their own permittivity (ϵ_r), conductivity (σ), and mass-density values. Canonical tissue models are often used to speed up simulations, and to ease the design of implantable antennas. These may be a single layer [32], thus accounting for a generic tissue- implantable antenna. They may also be multilayer [33], thus providing a simplified model of a specific implantation site inside the human body As antenna design is concerned, it is important to highlight that multilayer canonical models have proven to provide an acceptable model for the human body. Highly similar return-loss characteristics have been found for implantable patch antennas inside a three-layer planar geometry and a realistic model of the human chest [34], as well as inside a three-layer spherical and an anatomical model of the human head[35].

VIII.FABRICATION OF THE MODELS

Biocompatible materials used commonly in some laboratories as dielectrics with similar electrical properties may be selected for prototype fabrication. For instance, Rogers 3210 (ϵ_r =10.2 , tanδ=0.003) is often used because of the resemblance with the biocompatible ceramic alumina (ϵ_r =9.4 ,tanδ = 0.006) [36]

SECTION III

I. IMPLANTABLE ANTENNA DESIGN AND MEASUREMENT

A. Antenna design

For implantable antenna designs, commercially available simulation softwares such as High Frequency Structure Simulator (HFSS), CST Microwave Suite, IE3D etc are used as the surrounding environment of implantable antennas are very complicated. Spherical dyadic Green's function (DGF) expansions and finite-difference time-domain (FDTD) code are used to analyze the electromagnetic characteristics of implantable antennas inside the human head and body. In order to make simulations more efficient, one-layer skin model is widely used for implantable antenna design. Besides one-layer skin model, three-layer tissue (skin, fat, muscle) model and 2/3 muscle model are also typical biological tissue models for implantable antenna design[37].These simple models not only make the simulation more efficient but also make the measurement easier, as these models can be made by mixed materials to meet the accurate permittivity and conductivity at required frequencies. so measured results in the mixed phantom can be compared with simulated ones with the same model thus to evaluate the design concept. In order to study the design in realistic environment, implantable antennas can be evaluated within accurate human body models, such as Gustav voxel human body[38]. model, as shown below in fig10. In fact, as for particular biomedical applications, implant positions and depth could be different. In this condition, simplified one-layer skin or three-layer tissue model may have low accuracy for antenna design. Accurate human body model is very needed for specific applications, such as wireless endoscope systems and neural recording systems.

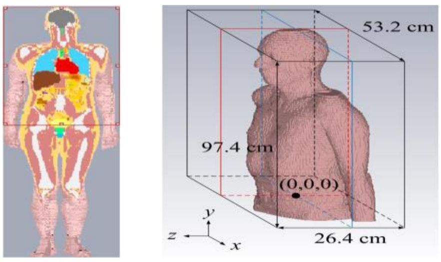


Figure 8:Three dimensional gustav vox model [37]

ISBN: 978-93-86171-36-8

B. Antenna measurement

1) **In-vitro measurement:** for general purposes one-layer phantom is utilized to design implantable antennas. And the implantable antennas are in-vitro measured in the one-layer liquid/solid phantom

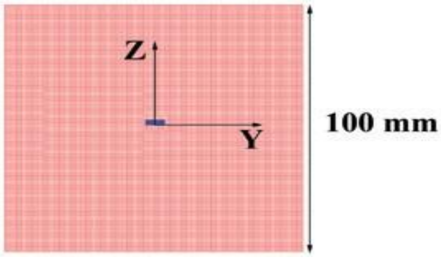


Figure 9: A single-layer canonical (skin cube) tissue model [34]

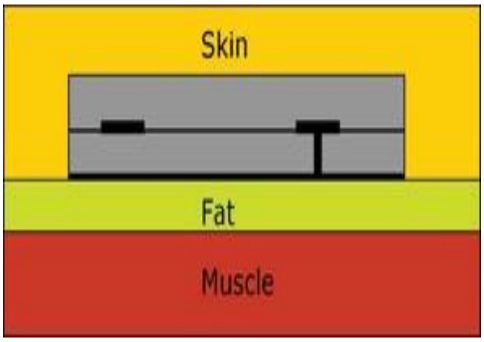


Figure.10: A simple three layer human tissue model[34]

Table Ⅰ. A comparison of the volume occupied by MICS implantable patch antennas reported in the literature, with respect to the miniaturization techniques employed.

Ref	Substrate Shape	Implantation Tissue	Bands [MHz]	Miniaturization Technique				Vol. [mm^3]
				Dielectric Material	Patch Shape	Shorting	Patch Stacking	
[33]	Rectangular	Skin	402-405	Rogers 3210 (1)	Spiral	–	–	10240.0
[33]	Rectangular	Skin	402-405	Rogers 3210 (1)	Spiral	yes	–	6144.0
[12]	Rectangular	2/3	402-405	MACOR® (2)	Spiral	yes	–	3457.4
[35]	Rectangular	Skin	402-405 2400-	Rogers 3210 (1)	Meandered	yes	–	1265.6
[23]	Rectangular	Skin	402-405	Rogers 3210 (1)	Spiral	yes	–	1200.0
[34]	Circular	Skin	402-405	Rogers 3210 (1)	Meandered	yes	yes	203.6
[18]	Circular	Skin	402-405	Rogers 3210 (1)	hook-slotted	yes	yes	149.2
[17]	Circular	Skin	402-405	Rogers 3210 (1)	Meandered	yes	yes	110.4
[15]	Circular	Skin	402-405	alumina (3)	Meandered	yes	yes	32.7

(1) ϵ_r = 10.2 , (2) ϵ_r = 6.1 , (3) ϵ_r = 9.4 ; * O. Quevedo-Teruel, personal communication

TABLE. II. PERFORMANCE COMPARISONS OF DIFFERENT ANTENNAS

References	Journal	Antenna Type	Operating frequency	Dimensions(mm^3)	Measured Bandwidth	Miniaturization method	Simulation model
[33]	2004 TMTT	PIFA	402 MHz/2.4 GHz	32×24×4	-/-	PIFA	One-layer skin
[32]	2008 TMTT	PIFA	402 MHz/2.4 GHz	22.5×22.5×2.5	35.3%/ 7.1%	Meandered PIFA	One-layer skin / three-layer tissues
[15]	2012 TAP	PIFA	402 MHz/ 433 MHz 868 MHz/ 915 MHz	$\pi \times 6^2 \times 1.8$	6.7%/6.5%/ 4.4%/4.4%	Meandered PIFA	One-layer skin/ 3-layer head/3D head
[29]	2013 TMTT	UWB	4 GHz	23.7×9×1.27	-	-	adult brain

TAP: IEEE Transactions on Antennas and Propagation

TMTT: IEEE Transactions on Microwave Theory and Techniques

EL: IET Electronics Letter

MOTL: Microwave and Optical Technology Letters

AWPL: IEEE Antennas and Wireless Propagation Letters

MAP: IET Microwaves, Antennas & Propagation be compared with the simulated results to evaluate the design concept. Parameters like reflection coefficient, path loss, communication link, polarization factor, can all be measured in vitro.

2). **In-vivo measurement**: As one-layer phantom model is not a realistic multi-layer tissue environment because the electrical properties of live tissues depends on frequency, temperature, age, size, sex of the subject . *In-vivo* testing is required to investigate the effects of the live tissues on antenna performance[39-43] .A dual-band implantable antenna operating in MICS and ISM (2.4-2.48 GHz) bands was tested in vivo[44]. A wireless completely implantable device in operating at the ISM band of 2.4 GHz was developed and tested. In-vitro and in-vivo evaluations were described to demonstrate the feasibility of microwave pressure monitoring through scalp[45]. Two implantable antennas were tested inside three different rats. And inter-subject and surgical procedure variations were found to quite affect the exhibited reflection coefficient frequency response[46].

ISBN: 978-93-86171-36-8

Apart from in-vivo testing in rats, an implant biocompatible capsule device in was implanted in a pig for in vivo experiment of temperature monitoring [47].

SECTION IV:

I. RECENT TECHNOLOGIES IN IMPLANTABLE DEVICES

1.1.Capsule Antennas

Comparing with implantable antennas, capsule antenna designs are more complicated because of the changing properties of the digestive organs of the human body when the antenna is ingested through the intestinal (GI) tract. various kinds of capsule antennas are designed to satisfy the needs of wireless endoscope systems, such as helical antenna[48] , patch antenna[49] , loop antenna[50].

II. INTEGRATED IMPLANTABLE ANTENNAS

Due to certain limitations where implantable devices have to be implanted in eyes or a human head, traditional implantable antennas are not small enough to be embedded into specific phantoms. So CMOS technology is used to further reduce the antenna size and achieve high integration of the whole implantable systems including implantable antenna and RF circuits on the same chip. Two separate antennas for wireless data communication and power transfer were integrated together to further reduce the antenna size. A triple-band implantable antenna was designed with data telemetry (402MHz), wireless power transmission (433 MHz), and wake-up controller (2.45 GHz*)*

III. IMPLANTABLE ANTENNAS FOR WIRELESS POWER TRANSFER

Generally in implantable antennas if battery is very low to maintain its operation, We have to perform surgeries to replace the battery, such as in pacemakers. In such cases wireless power transfer is a very innovative way to replenish the power in the batteries of the implanted devices. Hence while designing implantable antennas rechargeable rectennas can be considered, by which wireless power transfer in implanted studies are done[51].

IV.CIRCULARLY POLARIZED IMPLANTABLE ANTENNAS

For communications in far-field RF-linked telemetry are obstructed by effects of multi-path distortion. so a person who is moving around during telemetry sessions such nulls of polarization mismatching may be prominent and of short duration if both transmitter and receiver antennas are designed with linear polarization. In such scenarios, implantable antennas with circular polarization is very much required[52-53].

SECTION V:

I. LAPSES OF IMPLANTABLE ANTENNAS

1.Bulky size at low frequencies: At low frequencies of <100MHz the size of implanted antennas becomes big due to increase in the wavelength.

ISBN: 978-93-86171-36-8

2.Antenna efficiency: Ideally, implants have to be in the range of 1 to 10 mm in diameter for a length of 5 to 35 mm, in order to facilitate the surgical procedure, while in the MedRadio band the free space wavelength is around 74 cm, and in the ISM band it is around 12 cm. This proves that implantable antennas must be heavily miniaturized, however by decreasing the electrical size of an antenna will lead to decrease in its electromagnetic performances, and many studies focus on how to obtain a good compromise between size and performances . All these studies consider however lossless (or low loss) miniature antennas radiating into free space. In the case of implantable antennas, we have an important change of paradigm as the antenna is directly surrounded by biological tissues. The main quality criterion in the design of such antennas is not the bandwidth or the radiation efficiency but the power transmitted out of the host body by the antenna. The efficient design of such antennas will thus have to take into account the host body, and will have to develop specific strategies in order to achieve this goal [54].

3. Selection of frequency bands**:** Though medical implants are reliable because there is little redundancy for sensing, transmission and forwarding. on the other hand, although ,it has more frequency bands to select than general WSN, because the bands are narrow and conditional license. for example, wireless medical telemetry service(WMTS)band can only be used in license hospital, clinics and not at home [55].

CONCLUSION

In this paper, I have tried to present a brief overview of the challenges faced and solutions suggested regarding the design, simulations and limitations of implantable antennas for biomedical applications. Design of implantable antennas focuses mainly on miniaturization and biocompatibility, though electrically small antennas present poor radiation performance and relatively narrow bandwidths. Gain enhancement is considered crucial because it compromises the systems overall performance. Power conservation to extend the lifetime of the implantable medical device is also one area where work is going on. Patch antennas are basically based on two numerical models that is the Finite-Element and Finite-Difference Time-Domain Methods .Simplified tissue models have shown to be able to substitute for complex anatomical tissue models, hence speeding up simulations. Though a homogenous model suffices for basic antenna designs, more realistic models are needed to refine the final antenna design and to provide accurate results. Efficient and accurate simulation tools for tissue models must be used for design and performance analysis. For testing inside tissue-mimicking phantoms we need to deal with the formulation and characterization of the tissue-mimicking gel. For frequency dependent tissue electrical properties, testing in animal tissue samples are performed. But the biggest hurdle lies in testing within living animals, for which many considerations are required for developing the necessary testing protocol. It must also be noted that the shape of the implantable medical device and the intended implantation site will actually determine type of the antenna to be used. Patch antennas are appropriate for integration into flat implantable devices only. For other than flat surfaces different modifications of patch antennas like spiral radiator, differentially abled antennas etc may be used. The challenges are limited in implantable antennas designs like efficiency and size limitations, however as advantages are more work must be further carried on with implantable antenna designs.

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