REVIEW ARTICLE

Exploring SAR Analysis of Implantable Antenna in Biomedical Applications: An Overview

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ABSTRACT

Continuous electromagnetic (EM) exposure from implantable antennas can cause tissue heating, making Specific Absorption Rate (SAR) a critical safety metric. This paper provides a generic overview of the SAR analysis for implantable antenna in the head, heart, breast, and limb regions, emphasizing impact of tissue composition on SAR values. Reported studies revealed that breast muscle tissue exhibits the highest SAR due to their complex layered structure, followed by the skull layer of head, and fat layers of limbs, and muscle layers of heart. To further quantify these effects, SAR in arm fat and muscle tissues is evaluated under varying input power levels. Results indicate that reducing input power from 0.1 W to 0.04 W lowers SAR by 36% in fat and 81% in muscle, highlighting the strong dependence of SAR on both input power and tissue type. Thus, analyzing antennas in varying parameters is crucial for implantable antennas to exhibit a regulated SAR value.
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INTRODUCTION

Remarkable advancements have been witnessed throughout several decades in the field of medical due to the emergence of advanced technologies. In particular, biomedical devices have been a groundbreaking innovation in healthcare due to their ability to monitor distinct vital signs or physiological data, such as blood pressure, respiratory rate, blood oxygen saturation, heart rate, and blood glucose level (1). Biomedical devices are classified into two groups based on the requirement of power and its applicability such as implantable or on-body. For instance, implantable defibrillators, neurological stimulators and cardiac pacemakers are some of the implantable devices that require power (2). Although the power required by these devices ranges from a few microwatts to tens of milliwatts, it is noteworthy that, the power is supplied by the external station that is connected through wires. To realize the wire connection, surgical procedures were carried out, however, they posed risks such as hazard or infection to the patients. As an alternative, the utilization of communication techniques has yielded unprecedented achievements in the medical field, resulting in the salvation of millions of individuals from threatening diseases (3).

This has been achieved by implementing the antenna, owing to their ability to provide power wirelessly and monitor the physiological data in real-time. Not only that, but the antenna also facilitates the wireless transfer of data from the implant to the externally designated recording equipment in real-time by establishing a connection between them (1, 3). Hence, medical professionals can monitor the antenna wirelessly using a wireless interface (1). Thus, support telemedicine and reducing the cost and time associated with visiting hospitals. Moreover, the common chronic diseases related to the heart, liver and kidneys can be monitored continuously. For instance, the antenna in the leadless cardiac pacemaker enables the continuous monitoring of the heart rate of the patient by the medical personnel wirelessly and is able to detect and respond to abnormal heart rate, thus, saving the life of the patients (4, 5).

Despite the advantages, it must be noted that designing an implantable antenna poses some challenges as it needs to satisfy some of the significant characteristics, such as reduction of antenna size, biocompatibility, and compliance with the Specific Absorption Rate (SAR) standards (6). Among these characteristics, SAR is a crucial value that needs to be evaluated for designing implantable antennas for biomedical applications. This is because the implantable antenna emits constant electromagnetic (EM) radiation, resulting in tissue heating, owing to the high energy absorption (7). Therefore, analyzing the SAR value of the implantable antenna is mandatory to ensure the safe performance of the medical device within the human body.

The SAR limit of the human body is affected by several factors, such as power, antenna position, body parts and tissue layers. It is notable that, the increment in the power significantly increases the SAR value beyond the limit that has been set (8). In addition, the implantation of the antenna in different body parts results in different SAR values, thus, the antenna must be tested in varying body parts to ensure that the antenna satisfies the designated SAR limit for each region of the body. For instance, the head and limbs are the most widely studied body regions for implantable antennas. However, the peak in chronic diseases and cancer leads to the implementation of antennas in the heart and breast to maintain the heart rate and detect tumours, respectively. Furthermore, the implantation of the antenna within different tissue layers also influences the SAR value of the antenna and it varies significantly among others. For instance, fat tissue exhibits higher SAR values than muscle tissue at similar power levels (9). Consequently, antenna implantation in fat-rich regions may lead to elevated SAR levels compared to muscle-rich areas when subjected to the same power, and body parts. Hence, identifying these variations is essential for determining the most suitable tissue layers for antenna placement to ensure both patient safety and optimal device performance. Therefore, it is crucial to evaluate the SAR values of antennas with different power levels, tissue layers and body parts prior to fabrication to ensure the designated safety standards are met.

Therefore, this paper gives a generic overview of the SAR analysis of antenna specifically implanted in the head, breast, heart and limb regions. There are only limited studies on SAR analysis of different body regions that have been reported at the moment. However, to the best of our knowledge, there are no articles that provide a summary of the literature. Thus, an overview of research ideas that explores the SAR analysis of antennas within the head, breast, heart and limbs is presented. Furthermore, this review summarizes the series of steps of simulation and experimental evaluation of SAR for implantable antennas. By addressing these gaps, this article will guide future research towards safer and more efficient implantable antenna designs.

In this article, the general overview of SAR, and the limits set by the organizations in several regions according to body parts are discussed briefly. This is followed by the overview of the voxel body model that is offered by Computer Simulation Technology (CST) Microwave Studio, along with a discussion of the simulation and experimental steps involved in SAR evaluation . Subsequently, the SAR value of the antenna within the head, breast, heart and limbs is presented. In particular, a study is presented to investigate the influence of different input power and tissue layers of fat and muscle on the SAR value of the antenna implanted in the arm of the Gustav model. Finally, the future directions for reducing the SAR value of the implanted antenna are discussed.

SPECIFIC ABSORPTION RATE (SAR)

SAR is an indicator of the amount of EM energy absorbed by the whole body or given mass of the human body (1g or 10g of tissue) (10). The SAR can be calculated using Eq. (1) and can be expressed in watts per kilogram (W/kg):

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

where σ is the electrical conductivity of the tissue, |E| is the root mean square (RMS) value of the induced electric field, and ρ is the density of the tissue. Table I presents the SAR limits according to the different body parts and regions. From Table I, it is notable that each region follows a specific organization that determines the SAR limit for body parts. For instance, the United States of America (USA) follow the SAR limit set by the Federal Communications Commission (FCC), whilst countries in Europe follows the International Commission on Non-Ionizing Radiation Protection (ICNIRP). It is noteworthy that the SAR limit varies for the head or torso according to the weight of the tissue. For example, in USA the SAR limit of the head or torso is set to 1.6 W/kg for 1 g of tissue, whilst, in other countries, it is set to 2 W/kg for 10 g of tissue. Meanwhile, for limbs, the SAR limit is set to 4 W/kg for 10 g of tissue. Hence, the antenna must follow the designated SAR limit according to the body parts where the antenna will be implanted prior to the fabrication. This can be achieved using simulation software that will be discussed in the following section.

Table I: Allowable SAR limit according to regions and body parts (8)

Region	Organization or Body	Body Parts		
		Whole Body	Head or Torso	Limbs (W/kg)
USA	IEEE/ANSI/FCC	0.08 W/kg	1.6 W/kg	4 W/kg
Europe	ICNIRP	0.08 W/kg	2 W/kg	4 W/kg
Australia	ASA	0.08 W/kg	2 W/kg	4 W/kg
Japan	TTC/MPTC	0.04 W/kg	2 W/kg	4 W/kg

SIMULATION OF SAR OF IMPLANTABLE ANTENNA

The SAR value of an implanted antenna can be evaluated using voxel-based human models, which provide a highly precise representation of the human body. These models are created based on the images obtained using Computer Tomography (CT) and Magnetic resonance imaging (MRI). For instance, MRI generates highly detailed pictures of the soft tissues of the human body, as well as the metabolic processes operating inside. Based on the acquired data from each cross-section, an image is generated into various tissue types, such as skin, muscles, bone, and organs. These models are accessible in CST Microwave Studio. The CST offers 8 human models, such as Baby, Child, Gustav, Laura, Katja, Donna, Emma, and HUGO, with varying sizes, ages, and genders (11), as presented in Table II. Among these models, Gustav and HUGO are widely used. For instance, HUGO is utilized in a wide range of electromagnetic applications, including safety assessment of electromagnetic devices (12), verification of antenna performance for imaging purposes (13), and SAR calculation studies (14), owing to its ability to accurately reflects the anatomical structure of the human body in the form of digital data. Besides that, Gustav is an anatomically accurate heterogeneous and homogeneous body model that is utilized in estimating SAR and E-field distributions during antenna performance assessment (15, 16). For this reason, Gustav is also widely utilized in biomedical research to improve electromagnetic systems. Such applications include the assessment of interbody and intrabody wireless connectivity (17) study on tissues as a propagation medium for implant communication (18), and the visualization of energy density distribution in selected body parts (19). Moreover, each body model presented in Table II has a different composition of biological tissues, and so does the electromagnetic properties (20). Hence, the body model must be chosen based on the intended function of the implantable antenna within the patients. Despite these advantages, voxel models have limitations such as fixed tissue resolution that may not capture very fine anatomical details, potentially affecting SAR accuracy in small or heterogeneous tissue regions.

Table II: Voxel Body Models with their Characteristics (18)

Voxel body model	Age	Sex	Height (cm)	Weight (kg)
Baby	8 weeks old	Female	57	4.2
Child	7 years old	Female	115	21.7
Donna	40 years old	Female	176	79
Emma	26 years old	Female	170	81
Gustav	38 years old	Male	176	69
HUGO	38 years old	Male	180	103
Laura	43 years old	Female	163	51
Katja	43 years old	Female	163	62

The SAR simulation of implantable antennas in CST Microwave Studio involves a series of steps. First, the antenna is designed and optimized for the intended operating frequency. Then, a voxel-based human model is selected based on the anatomical location and application of the implant. The antenna is precisely placed within the target region, such as the head, breast, heart, or forearm to replicate realistic implantation scenarios. Appropriate excitation ports and boundary conditions are defined, and the input power level (typically ranging from 1 to 10 mW) is set. A refined mesh, particularly around the antenna and surrounding tissues, is generated to ensure simulation accuracy. The electromagnetic solver is then run to compute the field distribution, after which SAR calculations are enabled using standard averaging masses (1g or 10g) to determine both localized and peak SAR values. The results are analyzed through visual plots to assess compliance with safety standards. If required, the antenna design or placement is modified and simulations are repeated to ensure adherence to SAR regulations.

EXPERIMENTAL EVALUATION OF SAR FOR IMPLANTABLE ANTENNAS

A series of steps are involved in experimentally evaluating the SAR of implantable antennas to ensure accurate and safe assessment. Initially, the antenna is designed and fabricated to operate at the intended frequency. Subsequently. a tissue-equivalent phantom is prepared using mixtures that replicate the dielectric properties of human tissues such as skin, fat, and muscle, following standardized formulations. The implantable antenna is then embedded into the phantom at the desired anatomical position and depth to simulate realistic implantation conditions. Once positioned, a controlled RF signal is applied to the antenna using a vector network analyzer (VNA) or signal generator. The electric field measurements are collected using specialized probes, and the SAR values are calculated. The measured SAR values are then compared against simulated results for validation and must comply with established safety standards. If the SAR exceeds permissible limits, the antenna design or position is adjusted and retested. This experimental approach is essential for confirming the safety and reliability of implantable antennas before clinical use.

EVALUATION OF SAR VALUE OF IMPLANTABLE ANTENNA IN DIFFERENT BODY PARTS

The quantification of SAR of the implantable antenna is a necessary safety assessment that must be evaluated when designing antennas for biomedical applications. This section will provide an overview of the studies that evaluated the SAR values of the implantable antenna for four body regions such as head, breast, heart and limbs. The evaluation of SAR for each body part is discussed in the following subsections. Lastly, the comparison of SAR values in different body parts are compared based on the discussed studies.

Evaluation of SAR Value of Implantable Antenna in Head

Antenna for head-implanted medical devices is being widely explored and the performance are being analysed in terms of SAR. For instance, Turgut & Engiz (2023) analyzed the SAR for the head by varying the frequency, tissue type, power level, age and gender of the voxel model (20). The results indicated that the adult male (0.05–5.15 W/kg) exhibited the highest SAR for 10 g of tissue, followed by adult female (0.03–4.46 W/kg), child (0.07–3.67 W/kg) and baby (0.06–1.75 W/kg) at 1800 MHz. Conversely, the SAR values for adult males (0.002–1.82 W/kg), adult females (0.002–1.57 W/kg), children (0.003–1.42 W/kg) and babies (0.003 to 1.02 W/kg) is comparatively lower at 900 MHz. It is noteworthy that the SAR of adult male, female and child voxel models at 1800 MHz exceeds the standard limit of 2 W/kg. Meanwhile, in terms of tissue types, the head exhibits a higher SAR value than the muscle, and fat regardless of the age and gender of the voxel models. In addition, the power level was varied from 1 W to 1.5 W at 900 MHz and 1800 MHz. It was reported that the SAR values of the voxel model within the limit at 900 MHz, however, at 1800 MHz the SAR value of the voxel models at different tissue layers exceeded the limit. Hence, different demographics, power, frequency and tissue layers significantly affect the SAR values, however, in this study, the SAR of the skull layer is not evaluated.

Therefore, Sapari et al. (2022) evaluated the SAR value of implantable antenna for the skull layer with input power of 1 W for 1 g and 10 g of tissue (21). It is reported that the SAR values were significantly higher (240 W/kg and 59.4 W/kg) at 4 GHz for 1g and 10g of tissue, respectively. To resolve this issue, the maximum allowable input power was reduced and set to 5.9 mW for 1 g and 33.6 mW for 10 g of tissue to ensure the obtained SAR values were within the limit. In addition, the experimental testing revealed that the SAR at 2.45 GHz (0.11 W/kg) and 5.8 GHz (0.42 W/kg) with the input power of 1 mW over 1 g of tissue are within the limit. This is done to ensure a thorough evaluation of the SAR in real-life applications to prevent any possible effects on the human body. Lastly, a patch antenna with L-shaped defected ground is proposed by Gupta et al. (2024) for the brain implant (22). The proposed antenna's SAR is evaluated by positioning within the brain phantom containing seven layers of tissue with an input power of 10 mW over 1 g of tissue. The obtained result indicated that the SAR of the proposed antenna which is 0.709 W/kg is within the limit, thus, the antenna is safe to be used as low EM energy is absorbed by the brain tissue.

Evaluation of SAR Value of Implantable Antenna in Breast

The most significant application of SAR analysis on the breast is the ability to detect tumours by measuring the absorbed energy of biological tissue from EM waves. Breast tumours are identified through localized regions with high SAR (23). In addition to the capability of detecting the presence of tumours, breast tumour location can also be determined via maximum SAR coordinates. Given this potential applicable in early tumour detection, there is growing interest in developing antennas suitable for breast health monitoring applications.

In a study conducted by Wang et al. (2021), an implantable antenna was designed for detecting breast tumour recurrence in the Industrial, Scientific, and Medical (ISM) band at an operating frequency of 2.45 GHz (8). For this purpose, the antenna is implanted inside the muscle layer. SAR analysis of the proposed antenna design revealed a value of 340.42 W/kg, exceeding the acceptable IEEE C95.1:1999 standard of 1.6 W/kg. Thus, a reduction in maximum input power from 1 W to 5 mW was performed to achieve a SAR value of 1.58 W/kg. Such a method of lowering the input power to adjust the SAR value is similarly implemented in another study. A microstrip patch antenna operating at the Medical Implant Communication System (MICS) band was proposed by Singh et al. (2021) (24). The proposed antenna design was optimized for breast tumour detection in the skin layer. At a resonant frequency of 402 MHz, a low SAR value of 0.147 W/kg was obtained when the input power is 2mW.

While the two aforementioned studies only utilize one model, a study by Almosawy & Furkan Rabee (2022) carried out SAR calculations for their proposed antenna on two different-sized breast phantom models (25). A small and medium breast phantom model was used, wherein the antenna was positioned inside the fat layer for both models to detect breast tumours located in the glandular tissue. For this study, the SAR safety requirement recommended by the ICNIRP of below 2 W/kg per 10 g of tissue was successfully followed. Findings show that a SAR value of 0.0583 W/kg for 10 g of tissue was attained during analysis in the small breast phantom model. Likewise, a SAR value of 0.000852 W/kg for 10 g of tissue was acquired upon employment of the medium phantom model. A decrease in SAR value is observed as the breast size increases as examined by Chaurasia et al. (2024) (26). It is apparent that previous studies have varying sites of implantation within tissue layers. Chaurasia et al. (2024) further discuss the influence of dielectric properties of breast tissue on SAR value and other factors, such as type of antenna, intensity of radiation power, frequency, reflection, absorption, and scattering effects. Thus, implantable antennas for the breast have various variables contributing to changes in SAR value.

Evaluation of SAR Value of Implantable Antenna in Heart

The antennas implanted inside the heart, typically integrated with an LCP system in the right ventricle, require careful consideration of the radiation absorbed by heart tissues. The average SAR for 1 g/10 g of human tissue in cubic form must not exceed 1.6/2.0 W/kg (27). A fractal antenna design with a triple band frequency of 915 MHz, 2.4 GHz, and 5.8 GHz exhibited SAR values of 438, 285 and 127 W/kg for 1 g of tissue and 82.7, 63.2 and 39.6 W/kg for 10 g of tissue (27). The SAR value decreases with increasing frequency, while at low frequencies, a high-intensity surface current increases the radiating apertures, leading to a higher SAR value (27). In a study conducted by Faisal et al. (2022), the SAR was calculated according to both standards (1 g and 10 g of tissue) inside the heart of a heterogeneous phantom. For this analysis, the input power in the simulations was kept at 1 W (28). The SAR was measured at frequencies of 915 MHz, 1.4 GHz, and 2.45 GHz over 1 g of tissue. The highest SAR value recorded was 255.52 W/kg at 1.4 GHz. In another study, a square tri-band antenna was designed at frequencies of 0.402, 0.915, and 2.4 GHz (29). The SAR values achieved for this design at frequencies of 0.402, 0.915, and 2.4 GHz were 123.3, 189.9, and 797.5 W/kg, respectively, with an input power of 0.5 W. Meanwhile, in another study, the highest SAR recorded without an LCP system was 280.616 W/kg at 2.4 GHz (30). The lower SAR values are attributed to the spiral shape, which creates a low electric field around the adjacent tissue. Since SAR measures the energy absorbed by tissue based on the electric field, a lower electric field strength around the antenna leads to less energy deposition, resulting in reduced SAR (31).Consequently, spiral and loop-type antennas are considered excellent candidates for biotelemetric applications due to their reduced SAR values (30). Lastly, a zigzag planar antenna operating at an Industrial, Scientific and Medical (ISM) band of 2.4 GHz was proposed by Feng et al. (2022) (9). The SAR values for 1 g and 10 g of tissue are 32.3 W/kg and 10.8 W/kg, respectively, with a power of 1 W. To keep the SAR within a safe and manageable range, the antenna's maximum allowable input power should not exceed 62.5 mW (9). However, for implantable antennas, the input power limit is much lower, typically set at 25 μW.

Evaluation of SAR Value of Implantable Antenna in Limbs

Besides wearable antennas, implanted antennas are also getting equal attention from researchers for arms. A differential fractal antenna with two operating frequency bands of MICS (402-405 MHz) and ISM (2.4-2.48 GHz) was proposed by Fan et al. (2020) to be implanted inside the muscle layer of the arm (32). The antenna exhibits higher SAR values, which are 47.9 and 45.5 W/kg for 10 g of tissue for MICS and at 2.44 GHz, respectively. Hence, the input power of less than 41.8 mW was used to obtain the SAR value that satisfies the limit. Similarly, planar inverted-F antenna (PIFA) operating at 2.4 GHz with a footprint of 4 × 5.6 mm is adopted from the study conducted by Dewan et al. (2022) for the SAR evaluation (33). This implantable antenna was constructed using a three-layer geometry consisting of a copper patch layer, a biocompatible substrate made of Rogers RO3210 (ε_r=10.8, tan δ≈0.0027) and a ground plane. The truncated upper arm of the Gustav voxel model with a resolution of 2.08 × 2.08 × 2 mm^3 was used from the CST Microwave Studio software owing to the high computational resources, increasing simulation time and memory requirements, especially when fine meshing is applied around the antenna and tissues. The SAR was analyzed by positioning the antenna in the fat and muscle layer of the truncated model. For this study, the maximum allowable input power was varied by setting to 1.00 W, 147.70 mW, and 0.04 W for the 10 g of tissue (9, 34, 35). The obtained SAR value for the PIFA within the fat and muscle layers of the arm is presented in Table III. When the maximum allowable input power was set to 1 W, which is the default reference power, the SAR value of PIFA within both fat and muscle layers was increased drastically by 689 % and 376 %, respectively compared to the limit. The high SAR value reflects the increased absorption of EM radiation by human tissue (36). Thus, the power was reduced to 0.1477 W, which is the maximum allowable power of 10 g tissue (9). The resulting SAR value for PIFA within fat is still greater than the regulated SAR limit by 135 %. However, the SAR value for PIFA within muscle is reduced by 30 % compared to the determined limit. Nevertheless, the maximum allowable input power was reduced to 0.0400 W, which yielded SAR values that are 36 % and 81 % lower than the limit for the fat and muscle layers, respectively. Since the higher value of the maximum allowable input power, resulted in a greater SAR value

Table III SAR value for PIFA implanted in fat and muscles tissues with different maximum allowable input power.

Maximum allowable input power (W)	10 g-SAR (W/kg) of Tissue layers	
	Fat	Muscle
1.0000	31.5700	19.0506
0.1477	9.3911	2.8138
0.0400	2.54329	0.7620

than the standards, it poses a risk to the patients. Hence, the appropriate maximum allowable input power must be selected for the PIFA when it is implanted in different tissue layers. For this study, the appropriate maximum allowable input power for PIFA within fat is 0.04 W, while for PIFA within muscle is 0.1477 and 0.04 W.

Summary of the Evaluation of SAR in Different Body Parts

Based on the above-discussed studies, some are summarized in Table IV according to the standard maximum allowable input power of 1 W. This is to analyse how the varying body parts and tissue layers influence the SAR values of 10 g of tissue. From Table IV, it is evident that each type of tissue layer contributes to significantly different amounts of SAR values. For instance, the SAR value of the implanted antenna in the muscle layer of the breast is higher compared to the antenna within the muscle layer of limbs, whilst the heart muscles have the least SAR values. This is followed by the skull layer of head, and fat layers of limbs. The highest SAR values of antenna within the breast is owing to the denser glandular tissue and complex layered structure of the breast with varying dielectric properties. Conversely, the heart muscle consistently shows lower SAR values, likely due to its deep anatomical location, surrounding fluid-filled tissues, and better thermal dissipation capacity, which attenuate and distribute electromagnetic energy more efficiently. On the other hand, the fat layers show moderate SAR, although they possess high resistivity and lower thermal conductivity, which can lead to accumulated heating under long exposure times. These variations highlight the influence of anatomical composition and dielectric properties on electromagnetic energy absorption. Notably, all the SAR values exceeded the recommended limit, indicating a potential risk. Therefore, a thorough evaluation of the SAR values of the implanted antenna is required to mitigate possible risks associated with antenna implantation and ensure patient well-being.

Table IV Summarized SAR value of varying body parts and tissue layers with maximum allowable input power of 1 W

Refs.	Body parts	Frequency (GHz)	Tissue layer	SAR (W/kg) (10 g of tissue)
(18)	Head	4.0	Skull layer	59.40
(21)	Breast	2.45	Muscle	340.42
(29)	Heart	2.45	Muscle	10.80
This work	Limbs	2.40	Fat	31.57
			Muscle	19.05

CONCLUSION

The implanted antenna must exhibit a SAR value that is less than the designated limit to ensure safe operation within the human body. In this overview, the SAR, its limits, and the voxel body model offered by CST Microwave Studio have been discussed. Besides that, the SAR value of antennas in the head, breast, heart, and limbs are presented. In addition, studies of SAR evaluation in fat and muscle layers are discussed. Based on the study, it is found that the PIFA implanted in fat exhibits a higher SAR value for maximum allowable input power of 1 and 0.1477 W compared to the PIFA implanted in muscle. Meanwhile, the muscle layer only exhibits a greater SAR value for maximum allowable input power of 1 W. Thus, the appropriate power for PIFA implanted within the fat is 0.04 W and for muscle is 0.1477 and 0.04 W.

From the above-discussed articles and presented results, it is noteworthy that the majority of the studies fail to consider one or more factors like how different tissue layers, power level and demographic characteristics, such as age and gender affect the performance of the implanted antenna in terms of SAR. This is because addressing this gap is crucial to minimize the risk associated with implantation and evaluate its effectiveness across diverse populations. By doing so, more reliable, feasible, and universally applicable implantable antennas can be realized. In addition, the SAR values were comparatively higher at increased power level. This can be reduced by incorporating metamaterials like Artificial Magnetic Conductor (AMC), Split Ring Resonator (SRR) and Electromagnetic Bandgap (EBG), which will suppress the surface wave propagation, leading to reduced SAR by limiting backward radiation into surrounding tissues. However, challenges such as biocompatibility and achieving effective miniaturization without compromising performance remain significant. Hence, the integration of biocompatible materials and coatings, such as silicone, contributes to SAR reduction by improving the impedance match between the antenna and the surrounding tissue, thus enhancing efficiency and lowering reflected power. Not only that, these coatings also serve a dual function by preventing leaching of metal ions and ensuring long-term biological compatibility. Lastly, antenna miniaturization can be achieved through techniques such as substrate loading, the use of high-permittivity materials, meandered structures, and folded geometries, which reduce the antenna's footprint while maintaining its performance.

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