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Biomedical Telemetry Antenna Innovations: Progress, Uses, and Prospects for the Future

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ABSTRACT: Biomedical telemetry is, therefore, significant considering it facilitates prompt telecommunication as well as tracking of medical devices between centralized systems and patients. The availability and quality of communication of information are determined by the performance and selection of the telemetry antenna. This article analyzes the current state of BMA technology, aiming to extend the communication range and transmission speed of the data. The research article intends to contribute to the development of wireless technology. A plethora of antenna sizes are tackled from wearable to insertable antennas in addition to the improvements in materials and fabrication methods. The present review paper puts the thesis on only a few of the numerous biomedical telemetry antenna applications in healthcare, and these are the Internet of Medical Things (IoMT) and remote patient monitoring applications. It discusses case studies where better antennas had led to the creation of new therapeutic strategies, and diagnostic capacities, and had overall improved the quality of services. Therefore, the architectural problems of the existing designs are scrutinized, and this gives the other research areas the chance to be explored. A biological telemetry antenna is set to be the mobile edge computing solution that combines artificial intelligence, a 5G network, and edge computing. It also improves capital effectiveness over the transition period. Presentation makes it evident, why antennas are the essential component of the connected healthcare system and how antennas might redefine individualized care and the healthcare ecosystem. In conclusion, this research provides an extensive overview of the developments, uses, and future directions of biomedical telemetry antenna technology. It is an invaluable resource for academics, engineers, and medical professionals who seek to understand more about the evolving nature of this crucial component of modern healthcare systems.

1. INTRODUCTION

The implementation of cutting-edge technology in healthcare has never advanced at such a rapid pace, particularly in the area of biomedical telemetry antenna advances. In the field of medical research today, the development of biomedical sensors has been driven by the advancement of electronics, revealing their capacity to attach to or integrate with the human body. It is imperative to endeavor to diligently observe modifications in human vital signs, supply information to sustain the best possible health state and alert medical experts to potentially dangerous situations. The endeavor requires advanced healthcare monitoring tools, which have been made possible by this paradigm shift. This study explores multiple approaches and looks at various parts of the healthcare monitoring system. Privacy for health data is the goal. Healthcare monitoring systems' ability to collect and analyze patient data is a major factor in their rising popularity. Close monitoring of vital signs, information for optimum health, and quick action by contacting medical specialists in the case that the situation deteriorates are all made possible by this method. For this, implants of devices are used. These systems cannot function without availability, integrity, and secrecy. These qualities are necessary for the protection of health data. In order to secure and protect health information in healthcare monitoring, this article addresses data collection, transmission, storage, and access techniques.

Figure 1 shows how several sensors implanted at the right places could be used to track a patient's health in a hospital setting. Patients' medical records must be kept secure. Depending on the patient's needs and serious condition, a separate doctor may receive the data over the Internet and provide guidance. A WBAN system's security cannot be ensured unless the primary security and privacy requirements are satisfied [1].

The convergence of the "Internet of Things" (IoT) and "Wireless Body Area Networks" (WBANs) has led to advancements in healthcare monitoring. This convergence has given rise to a solid architectural foundation for creative solutions. IoT and WBANs are popular subjects in healthcare. These discussions also focus on privacy and security concerns related to IoT-driven healthcare monitoring. One obvious conclusion emerges from the discussion of healthcare monitoring systems: these systems, which make use of IoT technology, provide solutions that go beyond conventional methods, offering a reconsidered and enhanced method of healthcare monitoring. This paper's examination also looks at numerous healthcare monitoring applications and WBAN-implemented projects, which illustrates how widely these systems have been adopted. Healthcare monitoring systems are becoming more widely used and accessible, as seen by notable projects such as AID-N, Tmote Sky, Vital Jacket, eWatch, Mobi Health/Mobi Care, Bike Net, SMART, Health Gear, UbiMon, SATIRE, CoreNet, Alarm Net, and Code Blue.

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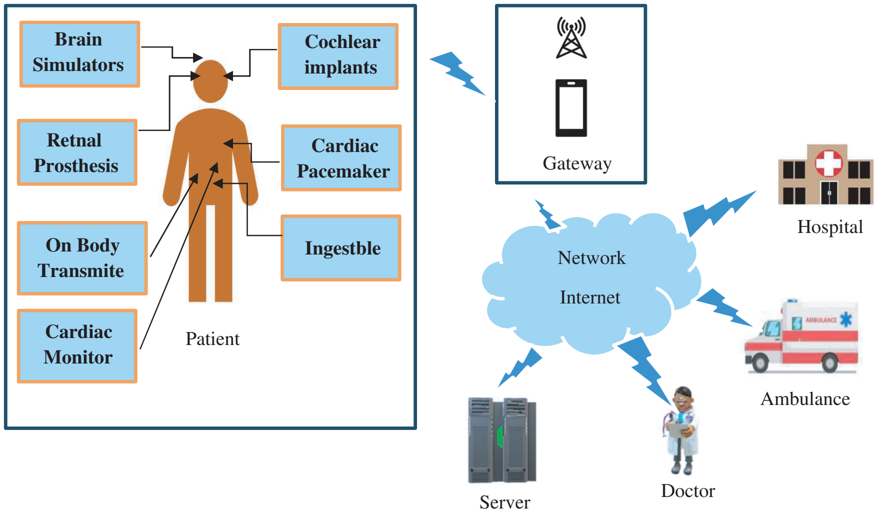

FIGURE 1. WBAN Architecture.

The study turns its focus to another area of innovation, which is the use of direct electromagnetic coupling for noninvasive assessments of simulated fracture healing, in step with the development of healthcare monitoring. In recognition of the importance of diagnostic monitoring and prediction in the healing process of bone fractures, the study presents a noninvasive measurement method that makes use of electromagnetic coupling. This method detects deflections in the hardware caused by applied loads by means of an antenna that electromagnetically couples with hardware that has been implanted. Here, the importance of this method of investigation as it was used for the ovine metatarsal bones, varying different degrees of fracture recovery shows the effectiveness of the method [2]. The utilized result endorses the system's ability to track the variations in sharing mechanical load between two sites, thereby being useful in both clinical evaluation and in making forecasts concerning fracture healing. By direct electromagnetic coupling method, non-implantable sensors are positioned as a better option in comparison with those that require implantation, thereby overcoming the long-term biocompatibility problems and demonstrating potential compatibility for use with the existing clinical hardware. Concurrently with the subject investigation of antenna improvements, the research also gives a design of patch antenna for on-body/off-body communication which has a square ring-shaped link together ground [3]. It pursues the field of bio-telemetry, i.e., the transmission of human readout data like body vitals and e.g., brain waves from the body to the external sensors. The proposed design is for a dual-mode antenna for both on-body and off-body communication after it is examined and refined on a multi-layered flat tissue phantom. The availability of the resonant frequencies which are strategically spread to cover LTE, ISM, and WLAN allows this antenna to be a solid mixture that integrates wide bandwidth and low specific absorption rate (SAR) to be tissue-safe. The end section acknowledges the design's potential for communications between bodies having carried out simulations and tests.

Transitioning from antenna design, the paper delves into the realm of fractal-based miniaturized hybrid fractal antennas for biomedical applications. The proposed GCHFA ("Giuseppe Peano and Cantor Set Fractals-Based Hybrid Fractal Antenna") represents an amalgamation of innovative design and optimization methodologies. Leveraging the Firefly algorithm for feed position optimization and a comprehensive dataset for performance evaluation, the GCHFA exhibits resonant frequencies conducive to biomedical applications in the Medical, Scientific, and Industrial bands [4]. To highlight the effectiveness of the suggested antenna, the research compares ANNs ("Artificial Neural Networks"), showing a near match between optimized, simulated, and experimental outcomes. Thus extending its purview even more, the study looks into how biomedical technology with implanted sensors will change healthcare systems in the future. Identifying the promise of WSN ("Wireless Sensor Network") technology and dividing body sensor networks into WBANs ("Wearable Body Area Networks") and IBANs ("Implantable Body Area Networks"), the session explains the paradigm shift from wearable to implantable sensors. Because these networks have complex architectures and are designed to monitor the elderly or people with chronic illnesses, they must be able to transmit data over a range of distances. The study also takes implanted sensor issues into account. Among these challenges are the requirements for invasive surgical operations as well as security, privacy, and moral use regulations.

Injectable biomedical devices, which use implanted electronics to monitor and stimulate body organs, are the subject of this study. Devices with unusual shapes, high aspect ratio designs, as well as the intention of being injected or implanted into internal organs are emphasized above bulky or flat formats. The study presented these injectable devices as novel devices in biomedical technology and explored their potential for neurological recording and stimulation. Following Biomedical Telemetry Antenna Innovations, challenges and potential directions are examined. The paper investigates the complex realm of biomedical technology and the ways in which new antennas and implanted sensors will influence healthcare infrastructures. Biomedical telemetry antennas could function better if they have complex optimization algorithms, AI, and machine learning built into them. It's possible for the monitoring systems to be more accurate and effective. The study highlights the need to address privacy, ethical, and regulatory issues in order to use new technology in a safe and ethical way.

The developments, applications, and bright future of Biomedical Telemetry Antenna Innovations are demonstrated in this thorough review. It also includes cutting-edge findings. Technologies such as implanted sensors, antenna design, and others are having a revolutionary effect on healthcare systems. This impact creates a more comprehensive image. We have the opportunity to reinvent medical monitoring and intervention, precision, accessibility, and ethics at the intersection of innovation and healthcare.

2. HISTORICAL BACKGROUND

Biomedical Telemetry Antenna Innovations' history has been characterized by both substantial technological breakthroughs and paradigm shifts in the healthcare industry. The term "telemetry," which describes the gathering and sending of data from a distance, was originally used in the early 20th century. Additionally, this is when the evolution first began.

2.1. Early Telemetry and Medical Instrumentation

Early in the 20th century, telemetry was a scientific field used in aviation and the armed forces. Communication technology advanced as it became possible to remotely monitor aircraft and weapons and transmit data. Medical instrument research was made possible by this novel telemetry.

In the middle of the 20th century, as electronic technology developed, scientists and doctors looked at the potential uses of telemetry in healthcare. The main goal was to create techniques for medical practitioners to transmit patient data and monitor physiological markers remotely. Early wearable sensors and telemetry devices were more constrained than those found in later technology.

2.2. Integration of Electronics in Healthcare

The use of electronic devices in the medical profession increased significantly in the last decades of the 20th century [5]. The advancement of microelectronics and sensor technologies has made the production of increasingly complex medical equipment possible. The development of integrated circuits, small sensors, and transistors made it easier to create devices that can monitor physiological signals.

2.3. Rise of Wireless Communication

The widespread adoption of wireless communication technology between the end of the 20th and the beginning of the 21st centuries marked a significant turning point. The 21st century officially began with this occurrence. This achievement brought about a significant change in healthcare telemetry and made the development of implanted sensors and WBANs feasible. New options for ongoing patient monitoring have emerged due to wireless connections, which offer the advantages of mobility and real-time data transfer. The use of wireless networks opens up many new opportunities.

2.4. Internet of Things (IoT) and Healthcare

Healthcare monitoring has changed as a result of telemetry, wireless networking, and the Internet of Things. The ability of the internet to connect medical devices and sensors allowed for easier data transfer and more thorough remote monitoring. The internet's strength to connect everything made this possible. It was found during this time that a variety of healthcare applications were making use of contemporary telemetry systems. Patient monitoring, diagnostics, and customized therapy were some of these applications.

2.5. Advancements in Antenna Design

The potential of biomedical telemetry technologies needed to be expanded at the same time that advances in antenna technology were required. As antenna technology has advanced to meet the unique needs of both on-body and off-body communication, it has replaced the traditional large, bulky antenna designs with more compact, efficient ones. Biomedical telemetry systems have experienced improvements in transmission range and signal quality due to the employment of innovative antenna configurations.

2.6. Implantable Sensors and Biomedical Technology

The idea of implanted sensors has gained appeal due to the decreasing size of electronic components brought about by technological advancements. A subclass of body sensor networks known as IBANs was developed to enable the implantation of sensors within human beings. This shift in the healthcare paradigm made it easier to monitor and treat chronic illnesses over time. The implanted biomedical sensor is a little device utilized for monitoring diverse physiological characteristics. Wireless connectivity allows for the collection and transmission of medical data by utilizing biocompatible materials, advanced design, and technology such as microelectronics. The structure of implantable biomedical sensor is shown in Figure 2.

2.7. Current Landscape and Future Prospects

Technologies for biomedical telemetry antennas are developing quickly. Telemetry systems are improved by AI, machine learning, and complex optimization algorithms, allowing for more precise diagnosis and individualized treatment. Healthcare monitoring and intervention will change as biomedical telemetry develops because smaller, more intelligent, and efficient systems will be created.

Biomedical Telemetry Antenna has been consistently innovated as electronics, wireless communication, and healthcare come together. This intersection has led to advances in technology. This journey demonstrates the never-ending goal of utilizing technology to enhance the caliber of medical care and influence the direction of healthcare provision in the future. It starts in the early days of crude telemetry and goes on to the present when healthcare systems are intricately linked.

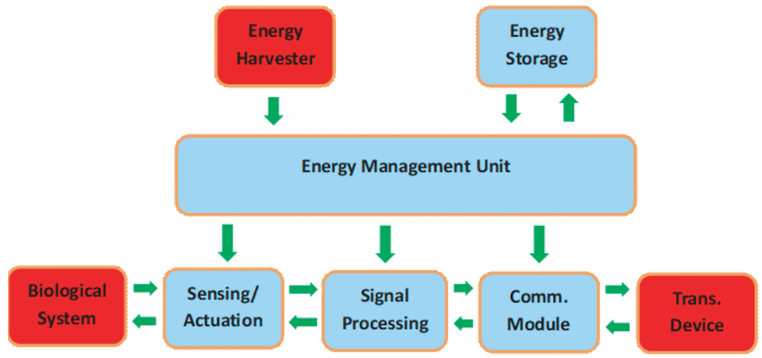

FIGURE 2. Block diagram of the implantable device [6].

3. RELATED WORK

In the field of biomedical engineering, a large number of research papers exploring novel applications, technologies, and techniques were published in 2019. The interdisciplinary nature of the field and its possible influence on healthcare were established by this study. Research on the need to preserve confidentiality and integrity in WBANs for remote healthcare monitoring addressed many important privacy and security issues. Another emphasized the use of noninvasive stability assessment in fracture healing simulations as a potentially useful clinical tool that has advantages over implanted sensors.

A patch antenna was constructed to address the need for wide bandwidth and low Specific Absorption Rate (SAR) to ensure safe tissue contact. This solution was tested on a tissue phantom for on-/off-body communication. Biomedical bands demonstrated the omnidirectional capability of small hybrid fractal antennas on the basis of Cantor set as well as Giuseppe Peano fractals.

A study outlining implantable sensors' implications for healthcare systems' future and emphasizing their function in early disease identification and monitoring attracted attention. Accurate resonant frequencies were demonstrated by the incorporation of ANN into the compact dual-band hybrid fractal antenna design [7].

Real-time physiological data was emphasized in research on wearable biosensors' potential for healthcare monitoring. A comprehensive review of several printing methods and their uses was provided by the investigation of the advent of three-dimensional printed sensors for biomedical applications.

The manufacture and implementation of silicon-based sensors in sensing prototypes were the main topics of discussion about these sensors' potential for use in biomedical applications. A novel technique for implanted radio frequency antennas was the use of bio-based dielectric substrates made of PLA ("Polylactic Acid") and SCS (Sunflower Carbon Substrate).

An extensive assessment was conducted on AoC (Antenna-On-Chip) technology, examining its advantages, drawbacks, and potential uses in new wireless technologies [8]. Also, the 2.45 GHz microstrip patch simulated effect that was realized for biomedical involvement (8) permits it to be used in an on-body matched state.

3.1. Formulation of the Problem Statement

The goal of this research is to provide a framework for the utilization of bioinformatics in the biomedical space-based data industry. This implies trying to improve the data mining techniques and antenna technology. According to these aspects, assuring data management efficiency and reliability, particularly in view of wearable and implantable devices, successful data analysis, and interpretation of large biomedical datasets require state-of-the-art data mining algorithms as one of the major difficulties. It turns out that the complexity of data collection with high biomedical is multifaceted and cooperative efforts that are directed at exploring the capabilities of software and hardware components would be a good starting point for this issue statement recognition.

3.2. Specific Goals

1. **Examining Modern Antenna Technologies:** It is the purpose of this goal to find a current study of the antenna design in the field of medical telemetry. Conversely, the course is focused on studying how technology is used in healthcare solutions, understanding the technological operations, and determining if it is improving the standard of care.
2. **Investigating the Integration of Bioinformatics and Data Mining**: The major idea is the exploration of bioinformatics and data mining techniques for the problem of big data in telemetry data processing and analysis. The strategies efficiently tend to be explained by the most recent investigations in optimization methods as their practical application in healthcare systems is being discussed in this research.
3. **Examining Difficulties in Antenna Technology**: We seek this objective to reveal and solve the multitude of barriers in antenna technology that may form a hindrance to their clinical use. One obstacle of these technologies is to establish biocompatibility and signal integrity, and the other is to modify the developed systems for different clinical purposes.
4. **Forecasting Upcoming Changes:** Predicting future trends and advancements in biomedical telemetry is the main goal for this purpose. It focuses on how

cutting-edge technologies like AI and IoT have the potential to completely transform the way healthcare is delivered, improving patient care through accessibility, personalization, and efficiency.

4. CHARACTERISTICS

The nature of antennas has to be good in case implanted or external biomedical devices have to send in data to the existing monitoring system. Here are some characteristics that are required for biomedical telemetry antennas: Here are some characteristics that are required for biomedical telemetry antennas:

Biocompatibility: Body-worn antennas must be biocompatible. The antenna material, whose safety and biocompatibility are achieved through apportioning nontoxic, nonallergenic, and biocompatible substances, nullifies adverse responses or tissue rejection. Moreover, we attempt to make the surface of the antenna retain any adhesion of bacteria or biofilm growth.

Power Efficient: Biomedical telemetry antennas have to have lower power consumption which is going to be accomplished by using low-power transmitters and the using smaller antennas. Proper energy management is the priority when it comes to continuous monitoring and lifetime extension of batteries by eliminating or at least reducing the battery replacement or recharge frequency.

Miniaturization: To include biomedical telemetry antennas in mobile devices or in body implants they should be super light and small. Minimization is necessary in this case to ensure that the antennas do not create problems by preventing the implanted device's functioning or making the person wearing them uneasy.

Wideband Operation: The Biomedical telemetry antennas should be able to adjust simultaneously to various communication standards as well as environmental conditions under which they operate. Broadband antennae offer flexible and versatile communication means that cover a wide range of applications and provide uninterrupted and seamless data transmission, as any challenges that may occur.

High Data Rate and Reliability: Biomedical telemetry antennas are in charge of imitating physiological data to the human being in real-time. This implies designing them to minimize the interference of signals and noise, which helps to create continuity in communication between the enclosed or worn device and the external monitoring system.

Flexible and low-profile design: The antennas used for wearable biomedical instruments should be positioned as close to a user flatly as possible. Also, the antennas should be very compact and flexible as a concern of comfort. Modification on an antenna design would permit stretching or bending of the device without interacting with its performance.

Security and Privacy: With the implementation of wireless biomedical devices becoming more common, one of the factors that should be given priority is the security and privacy of data. In order to ensure the security of patient's medical information being transmitted from within the device to systems outside of it, antennas should have the ability to encrypt data and perform authentication.

External Resilience: The pipeline procurement engineering group will be able to eliminate the interference of electromagnetic radiation, temperature fluctuations, water presence, and mechanical damage of the biomedical telemetry antennas. Platitudes to antenna efficiency assure fruitful work at any environmental conditions and thus allow prolonged life expectancy for implant and worn device.

Compatibility with Existing Infrastructure: Biomedical telemetry antennae should be interchangeable with the devices that are widely used in present patient care communications to ensure that they are just what healthcare systems can cope with and can easily be adopted.

Cost-Effective: Although long-range data transmission from portable devices used in biomedical telemetry is possible, it is crucial to understand the cost-effectiveness of specific antenna designs. This is probably the reason behind the successful deployment of business owners who have interest in this market. The antennas for satellites must be cheap to make and should be made of ordinary, low-cost materials and simple manufacturing processes which will work both reliably and perfectly.

Scientists and engineers can enrich the usability of wearable and implanted medical devices as well by including these requisites in biomedical telemetry antenna design, thus contributing to better monitoring, diagnosis, and treatment of diverse health issues.

5. LITERATURE REVIEW

Many research works that have created a substantial contribution to the neuro-medicine technology field show that lots of studies on wireless systems are done. Moreover, the design of medical devices should not only raise their acceptability but also increase their usefulness while dedicating high attention to miniaturization, safety, and performance of the human body.

The opportunity, problems, and the future possibility of AoC for creating wireless systems were surveyed by a report at the end of 2019. AoC, or off-chip antenna technology, has been a topic of a lot of discussion lately because of its many advantages over alternative antenna technology. Among these advantages are miniaturization, low power consumption, affordability, and superb wireless module integration. To fully realize the potential and valuable advantages of AoCs, this article provides a comprehensive overview of the advantages & disadvantages of AoCs for a range of emerging wireless applications, like biomedical implants, UAVs ("Unmanned Aerial Vehicles"), 5G wireless systems, autonomous vehicles, IoT wireless devices and systems, wireless energy transfer, wireless interconnects, WSNs ("Wireless Sensor Networks"), and RF ("Radio Frequency") energy harvesting. Likewise, the use of silicon sensors is a fundamental and well-established technique in many healthcare sectors [9]. These biomedical sensors are highly sig-

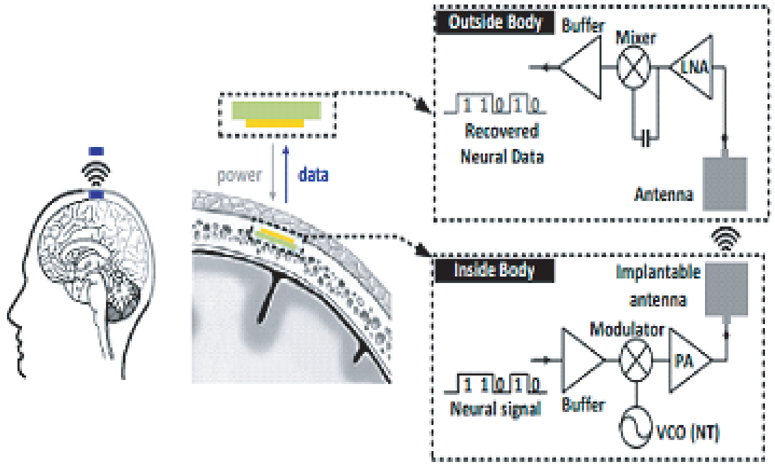

FIGURE 3. A wireless data link between a flexible patch antenna for biomedical uses [18].

nificant as they improve human life quality and contribute to the advancement of microfabrication by providing insights into creating superior multifunctional sensing prototypes. The sensing industry has reaped significant benefits from 3D printing methods due to numerous advantages, such as rapid production, user-friendliness, versatility, and sustainability, apart from emphasizing the importance and influence of three-dimensional printing techniques in the manufacturing of sensors for several medical uses [10].

A novel implantable antenna is introduced for wireless biotelemetry in medical device radio communications. It is compact and not affected by different implant placements within the human body. It has moderate gain, decent bandwidth, and return loss [11]. A three-band sticky antenna is designed for biomedical telemetry uses. The signal of an implanted medical device is frequently quite weak due to the lossy nature of the human body [12]. By acting as a repeater, the adhesive antenna increases the strength of the signal. As a result, the signal can effectively reach the base station. It includes the MICS band, ISM frequency, and IEEE 802.11 WLAN spectrum. A µLED, antenna, and integrated circuits were built within an electronic contact lens enclosed in polydimethylsiloxane (PDMS). The recommended antenna was self-tuned and required no additional equipment in the form of capacitors or inductors [13].

The current work suggests a new ultra-wideband microstrip patch antenna design for cardiac monitoring [14]. An increasing number of short-distance communication lines are using ultra-wideband antennas because of their large bandwidth and ability to carry large amounts of data. It uses less electricity, poses no health danger to people, and functions with accessories flawlessly. Its little power usage and excellent compatibility with peripheral devices come with a lower risk of radiation exposure for humans. A unique dual-band wearable antenna with a defined ground structure and rectangular parametric elements is proposed in [15] for telemedicine applications. The 890 MHz to 960 MHz and 1710 MHz to 188 MHz dual-band frequencies, which have extremely significant gain and are used in the Global System for mobile communications applications, are covered by this antenna. In [16], an exclusively connected split ring is proposed as a small antenna for wireless deep cerebral implants. With most energy-harvesting microsystems, the antenna's wide adjustable inductive impedance range provides the common values required to produce good complex conjugate impedance matching.

In [17], a compact, flexible monopole antenna that is wearable and designed for UWB frequency and ISM bands is suggested for usage in on-body and in-body communications. Compared with the recently published wearable flexible antenna topologies, the proposed monopole antenna is more straightforward, and compact, and provides higher radiation efficiency in terms of overall efficacy. An antenna's matching quality increases with proximity to the skin's surface. This important feature makes flexible antennas meant for body-area networks potentially useful in a range of situations as shown in Figure 3.

In [19], contemporary microstrip antennas designed for use in biotelemetry are illustrated. An overview of the main improvements made to Osseus, which uses a 2.45 GHz signal to classify bone mineral density and may potentially lead to an osteoporosis diagnosis. This paper describes an efficient focusing technique in [20] that uses noninvasive microwave imaging and hyperthermia to treat breast cancer. The organization of this technique is illustrated in Figure 4. PSO ("Particle swarm optimization") can be applied to calculate the optimal excitations (amplitudes and phases) for a 3D MSP ("Micro-Strip Patch") antenna array operating at 2.45 GHz. Achieving the required hyperthermia temperature (over 42°C) at the tumor location without causing hot spots in healthy tissues requires adjusting the antenna parameters to maximize power loss density and SAR at the tumor site.

In [21], a small FDPA suitable for biological implant applications and overheating is demonstrated. The suggested antenna provides impedance matching without the need for a complicated matching circuit or Balun transformer, and it is quite compact electrically. Prior to incorporating the lumped element into the folded dipole patch and adjusting the feed point, the antenna resonates at 2.65 GHz. The signal resonates at 434 MHz in the sub-1 GHz area. A unique flexible antenna working in the X-band has been presented in [22] for biological applications. It has a large bandwidth, excellent efficiency, and a high gain. With a wide 7 GHz bandwidth, the suggested printable

TABLE 1. Comprehensive summary of biomedical antenna research.

S. No	Year	Focus of Study	Technology Used	Key Findings	Applications
1	2019	WPT system for capsule endoscopy [29]	Implantable	Compliance with FCC's SAR values	Medical Telemetry
2		Bio sensers for health care monitoring [30]	Wearable	Wearable biosensor's reliability and stability	
3		Wideband flexible mono pole antenna [31]	Wearable	Performance stability under bending	Biomedical Telemetry
4		Flexible biosensing devices [32]	Implantable/wearable	Design fabrication and applications	Biotelemetry
5		Bio-Based Dielectric Substrate for Implanted Antennas [33]	Implantable	Bio-compatible material used for antenna	Medical Applications
7	2020	Compact circular polarized implantable ring slot antenna [34]	Implantable	Circular polarization with biocompatibility and compact size	Biomedical Telemetry
8		Meander Line Monopole Antenna for MIMO Applications [35]	Implantable	Circular polarization with good gain and compact size	
9		Flexible Multiband Antenna for Biomedical Telemetry [36]	Wearable	Flexible and compact with a good operating bandwidth of 5.1 GHz	Medical Telemetry
10		Coplanar waveguide (CPW)-fed ultra-miniaturized patch antenna [37]	Implantable	Two-way circular polarization and good impedance bandwidth	Biomedical Telemetry
11		Effect of a Superstrate on Antennas [38]	Implantable	Penetration power can be increased inside the body with lower SAR	
12		Wideband Fractal antenna for wireless capsule endoscopy [39]	Implantable	Compact size with flexibility and biocompatibility	
13		Hybrid fractal antenna with DGS [40]	Wearable	Can operate at S, C, and X bands with good directivity and gain	Medical Telemetry
14		Low-profile ultra-wideband antenna medical imaging systems [41]	Wearable	Wide bandwidth with compact size and good gain	Biomedical Telemetry
15	2021	Antenna design based on Gosper curve fractal geometry [42]	Implantable	Compact size with high gain is achieved using Gosper curve fractal geometry	Biotelemetry
16		Low-profile dual-band antenna for compact biomedical devices [43]	Implantable	Compact size with a low SAR rate	
17		Miniaturized antenna with a highly tuneable Input Impedance [44]	Implantable	Miniature antenna with tuneable impedance gives high bandwidth with varying frequency for capsule	Biomedical Telemetry

18		Miniature Implantable Antennas for Telemetry Applications [45]	Implantable	Narrowband miniature antenna using two bands with optimum bandwidth	Medical Telemetry
19	2022	Compact Meander Line Telemetry Antenna with Low SAR [46]	Implantable	Meander line technique with open loop configuration gives low SAR and reduced size for pace maker	
20		Implantable antenna for wireless cardiac pacemaker system [47]	Implantable	Folded meander structure with high dielectric constant medium reduces the size	
21		MIMO antenna for high data rate biomedical ingestible capsules [48]	Implantable	Compact MIMO antenna with high-data-rate and wider bandwidth	Biomedical Telemetry
22		Miniaturized antenna verified with diffuse optical measurements [49]	Implantable	Co-planar waveguide antenna is used for differentiating native and infected adipose tissue	
23		Compact Dual Band and Flexible Elliptical-Shape Implantable Antenna [50]	Implantable	Compact size flexible and dual band elliptical-shaped antenna with good bandwidth	
24		Triple-band implantable antenna design for biotelemetry applications [51]	Implantable	Improved bandwidth and all-time data connection with high-speed communication	
25		Dual-band rectenna system for biomedical wireless applications [52]	Implantable	Antenna design for power transfer using Pi marching network	Wireless Power Transfer
26		Dual-Band Dual-Polarized surface integrated wave Cavity-Backed Antenna [53]	Wearable	SIW technology used in antenna design which gives high gain with dual polarization	Medical Telemetry
27		High-Contrast Low-Loss Antenna [54]	Wearable	Biocompatible with high bandwidth for sensing and imaging	
29		Miniaturized Loop Conformal Antenna for Capsule Endoscope [55]	Implantable	Compact size with ultra-wide band width and circular polarization	Biomedical telemetry
30	2023	Highly compact CP implantable antenna using slots [56]	Implantable	Compact size with triangular slots gives high impedance bandwidth with CP	
31		Compact, Implantable, DualBand Antenna [57]	Implantable	Low profile dual band antenna with good gain using Koch fractal structure	
32		Planar Array of UWB Active Slot Antennas [58]	Wearable	Planar array for sensing and imaging of tumor	Medical Telemetry
33		Dual-band implantable antenna for wireless biotelemetry in arteriovenous grafts [59]	Wearable	Good bandwidth with compact size and low SAR value	

34	2022	Design of an Out-Folded Patch Antenna With a Zeroth-Order Resonance for Non-Invasive Continuous Glucose Monitoring [82]	Wearable	A high Q resonance with good bandwidth	
35	2023	Ultra-Wideband Fractal Ring Antenna for Biomedical Applications [83]	Implantable	A wide bandwidth and good impedance matching is achieved	Biomedical telemetry
36	2022	Wireless Powering and Telemetry of Deep-Body Ingestible Bioelectronic Capsule [84]	Implantable	A compact size with very good gain in both WPT and biotelemetry is achieved	

TABLE 2. Methodology for designing contemporary antennas.

Step	Description	Example Studies	Significance
Requirement Analysis	Understanding specific needs	Mishra et al. [85]	Customizing design for specific biomedical purposes
Material Selection	Choosing suitable materials	Aleef et al. [86]	Ensure biocompatibility and endurance.
Design and Simulation	Using CAD and simulation tools	Iqbal et al. [87]	Predicting behavior in biological contexts
Prototyping and Testing	Real-world testing of prototypes	Smida et al. [88]	Evaluating practical performance and stability
Compliance and Safety Testing	Ensuring regulatory compliance	Butt et al. [89]	Compliance with health and safety standards
Integration with Devices	Integrating with medical devices	Jiang et al. [90]	Ensuring effective operation in medical settings
Performance Evaluation	Assessing efficiency and reliability	Yousaf et al. [91]	Verifying operational effectiveness and dependability
Continuous Improvement	Iterative enhancements	Rahmat-Samii et al. [92]	Developing designs to meet changing medical needs

ERSPMA operates on three distinct flexible substrates. Furthermore, the antenna functions reliably when bent in four distinct directions.

A 4-antenna module in a capsule endoscopy is recommended in [23] for MIMO (Multiple-Input Multiple-Output) functioning in order to attain the goal of real-time transmission of high-resolution images at high data speeds. The projected design fits 4 antennas in the extremely limited space of the capsule endoscope by fully utilizing the interior wall space of the capsule body and using conformal architecture for compactness. To enable MIMO operation, 3 distinct technical methods are utilized to improve or decouple the isolation between adjacent as well as diagonal antenna parts. System considerations (interaction between the electronic components and the endoscope's antenna) and a SAR assessment are conducted to authenticate the robustness as well as human safety of the projected design, correspondingly. Through the use of the concepts of partial ground and metasurfaces in [25]. Given that the antenna has a 44% fractional bandwidth along with a radiation efficacy of more than 53% across the entire frequency range, its wideband characteristics are easily seen. Because it covers three bands — ISM, MBAN, and UWB — this antenna outperforms other varieties that academics have occasionally recommended for use in biomedical applications. Gain and axial ratio reduction are two more ways to improve the antenna's performance.

A 2-port MIMO antenna with circular polarization that is semi-rigid is designed for wearable applications [26]. Within the mm-wave broad frequency range in which the antenna operates, RHCP radiations are detected at 27.10 GHz and LHCP radiations at 29.53 GHz. The various 3 dB AR bandwidths are between 25.84 and 27.35 GHz and 28.57 and 29.85 GHz, respectively. The antenna's performance in bending profiles along the x- and y-directions showed durability, with a slight shift in the results to a lower frequency in comparison with the flat profile as the current on the radiating patch lengthens because of bending. In [27], a CPW-fed stingray-shaped UWB antenna element along with a 4-port MIMO antenna was implemented orthogonally without the requirement for a special isolating structure. With a 10 GHz bandwidth, the MIMO antenna operated in the frequency range of 4.4 GHz to 14.4 GHz. The overall gain of the antenna system is 5.3 dBi, and the isolation between the antenna's components is usually 22 dB. The suggested MIMO antenna design has great potential for integration into MIMO-based medical imaging systems, where antenna efficacy is critical. Furthermore, the design offers a powerful workaround that can improve wireless connection resilience. This helps with data transfer and meets the growing needs of modern consumer electronics. This article suggests integrating an ultra-compact MIMO antenna into the leadless pacing scheme to enable low-loss MIMO transmission to an external MIMO antenna for remote cardiac monitoring on a 5G IoT platform [28]. Here, two distinct designs of far-field communication systems — one with a single-port antenna and the other with a MIMO antenna — are used to test the low-loss capability of MIMO communication. The proposed MIMO antenna communication system is ideal for wireless power transfer for commercial leadless TCP systems and

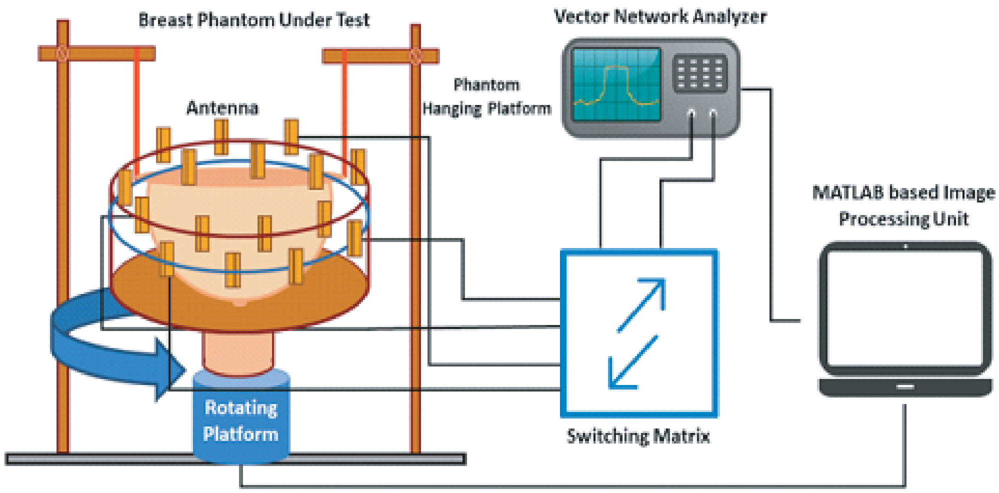

FIGURE 4. Microwave imaging system designed for breast cancer [24].

remote health monitoring because of its ultra-compact size along with the higher far-field received power in both frequency bands.

From above Tables 1 and 2, a comprehensive comparison and conclusion can be drawn to get the desired concept which is given.

Past vs. Present: Antennas have progressed from bulky, power-hungry equipment to tiny, energy-efficient components capable of transferring larger amounts of data.

Traditional vs. Innovative Uses: While remote monitoring and implanted devices were once common applications, innovations have broadened to encompass sports tracking and clinical research.

Current vs. Future Prospects: Current prospects include 5G integration and enhanced AI capabilities, whilst future prospects include improved biocompatibility and increased security measures.

Basically, redevelopment and further enhancement of biotelemetry antenna have highly expanded the usage of biomedical telemetry in remote monitoring, clinical research, and personalized care. Stepped-up developments of reducing dimensions, bandwidth, and energy consumption, as well as associating with emerging technologies will continue to create new possibilities for more productive and reachable healthcare services, thus benefiting millions of people all over the world.

Through the graph, we are able to notice that from the beginning biotelemetry antennas were quite big running low on energy. Now, however, they have been designed to make them smaller, more energy-efficient, and with the capacity to transmit huge information. Traditionally, biotelemetry technology is used for remote patient monitoring and IMDs (implantable medical devices). The future holds further progress in the field, allowing for it to also be applied in clinical research and athlete tracking, proving in this way its adaptability. Current trends include the integration of biotelemetry antennas with 5G and AI technologies, as well as future improvements in biocompatibility and security precautions.

In biomedical engineering, implantable medical devices (IMDs) are essential for treating and monitoring damaged organs. IMDs are made up of RF and electronic components, and their traditional power sources are direct current (DC) power supplies and batteries. To get around these issues, it has been suggested that IMDs be driven safely using wireless power transfer, or WPT [30, 84]. Research on the design, development, and use of biocompatible, flexible biosensors and antennas is expanding quickly. Their primary objective is to measure biophysical parameters, which include blood/intraocular pressure, temperature, pH, heart rate, brain signals, and air quality [31–34]. The advancement in biomedical telemetry required high data speed with dependability and quality. The MIMO systems are regarded as the future of new biotelemetry communication networks [37, 50, 93]. In biomedical telemetry, dual-band antennas improve signal reception, coverage, data transfer efficiency, and range. Their coverage and range are improved by operating on two different frequency bands. In congested wireless situations, dual-band antennas reduce interference by providing flexibility and adaptability. Communication systems become more dependable, effective, and resilient as a consequence [45, 52, 54, 55, 62].

Biomedical telemetry can benefit greatly from fractal antennas' compactness, wideband operation, multiband capabilities, resilience to environmental changes, improved signal quality, and customizability. They are perfect for many applications since they are small, take up little space, and function throughout a wide frequency range. In addition to mitigating the influence of surrounding materials, their self-similar shape ensures reliable data transfer [41, 42, 44, 83]. Broadband antennas excel in biomedical telemetry because they provide high data speeds, compactness, reduced interference, improved signal transmission, broad frequency coverage, and simplified systems, making them ideal for integration into wearable or implantable medical devices to improve patient comfort and mobility [43, 61, 83, 90, 94]. In capsule endoscopy, conformal antennas include decreased interference, omnidirectional radiation, compactness, biocompatibility, and improved signal transmission. Non-invasive deep tissue monitoring, continuous monitoring, wireless data transfer, and enhanced diagnosis and therapy are all made possible by the Deep-Body Ingestible Bioelectronic Capsule [50, 58, 87, 91, 92].

Biomedical engineering has seen innovative research in a number of fields. Innovative technologies like electronic contact lenses [65], implantable pressure sensors [64], injectable biomedical devices [60, 63], and flexible multiband antennas for biomedical telemetry [66] were the subject of studies. Capsule endoscopy has advanced as a result of research into antenna designs for ingestible applications [67]. The architecture of ingestble capsule used for deep body biotelemetry is shown in Figure 5. The creation of incredibly small, circularly polarized implantable antennas as well as the research into how superstrates affect on-head matched antennas were two noteworthy contributions. Furthermore, UHF RFID tags for biomedical sensing were optimized [68], and miniaturized wideband ingestible antennas inspired by fractals were created for WCE (Wireless Capsule Endoscopy).

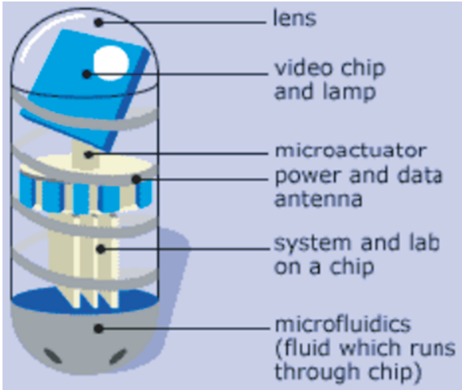

FIGURE 5. The system architecture of deep-body ingestible bioelectronics capsule [77].

A number of significant studies serve as examples of the explosion of innovative research in the field of biomedical engineering. The investigation of flexible, wearable, and mobile antennas [68] gained prominence and offered a thorough rundown of a variety of technologies, such as MIMO, planar monopole, and microstrip configurations. Additional ground-breaking research focused on smart contact lenses for biosensing applications [69], liquid metal-based soft electronics for wearable healthcare [70], as well as soft materials and devices for wearable healthcare [70]. The advancement of wearable and implantable intraocular pressure biosensors [72] and subcutaneously implanted devices for cardiovascular assessment via NFC [71] demonstrated a dedication to creative solutions in healthcare. Improvements in the application of metasurfaces for bioelectronics and medical technology were also made this year [73]. Optoelectronic devices for peripheral neural pathway phenotyping as well as the impact of beamwidth and antenna gain on screening of osteoporosis have advanced further [74].

As a result of several ground-breaking research publications, the field of biomedical engineering kept developing. Research examining nearfield radio links of normal mode helical antennas for WCE [75], compact and miniaturized implantable antennas for wireless cardiac pacemaker systems, and low-profile compact meander line telemetry antennas for pacemakers demonstrated the emphasis on antenna technologies for medical applications. An implantable, multichannel wireless telemetry system for photodynamic therapy was developed with significant assistance from artificial intelligence [76], demonstrating the technology's ability for successful treatment of cancer.

An enhanced compact circularly polarized implantable antenna has better performance and design guidelines for a circularly polarized bow-tie antenna specifically suited for ISM bands [78]. Other noteworthy works presented a multiband SSr diode RF rectifier [80] and a sub-1 GHz ultra-miniaturized folded dipole patch antenna [79] for biomedical applications, highlighting possible uses in powering low-power implantable devices. The improvement of miniaturized bio-implant antenna performance and its effects on bodily fluids in medical settings were the subject of another study [81]. The combined efforts of these individuals represent the dynamic development and continuing promise of biomedical antenna technologies.

6. OUTCOMES OF THESE TECHNOLOGICAL BREAKTHROUGHS IN MEDICAL SITUATIONS

1. Biomedical antennas are frequently employed in cardiac monitoring devices, such as ICMs (Implantable Cardiac Monitors) and ICDs (Implantable Cardioverter-Defibrillators). These devices feature antennae that are used for transmitting data which may include cardiac rhythm, electrical activity, and other important factors to external systems of health monitoring. For instance, an Insertable Cardiac Monitor (ICM) from Medtronic's Reveal LINQ network transmits an ECG report to a bedside monitor or a patient's smartphone with the use of a small antenna.
2. Several wearable health trackers are now available in the market today and these include fitness bands and smartwatches. What makes them special devices is their use of biomedical antennas, which make it possible for the fitness trackers to interact wirelessly with smartphones and other devices. These antennas help to assess on a long-term basis, body temperature variations, activity levels, and the way someone sleeps. Let us consider, that the latest Apple Watch Series 6 has the ability to detect heart rate directly with its built-in antenna, do an electrocardiogram (ECG), and check the oxygen levels of blood.
3. Biomedical antennas are vital parts of telemetric systems for medical use that let physicians watch over patients whose diseases are ongoing from their homes. Sensor equipped with antenna send data to the central monitoring system or physician's portal for continuous evaluation. Sensors allow for quicker detection of changes in vital signs and timely monitoring of a patient. Now, Philips' BX100 Biosensor connects to a personal care assistant via the cloud to track vital signs such as heart rate, breathing rate, and time activity by health service specialists remotely.
4. The WCE is the endoscopic examination which is absolutely non-traumatic and noninvasive for seeing nailed by camera of the stomach and intestine. BMED antennas are implanted on miniature cameras, which are impregnated in ingestible capsules that allow the transmission of video and image recordings to an external receiver worn by the patient wirelessly. The Medtronic biomedical antennas of the small bowel use high-definition pictures of it for proper diagnostic purposes.
5. Biomedical antennas find application in many implantable medical devices including ones that can deliver drugs, stimulate the nervous system, and regulate the heart. The antennas serve as the link-up between the in-body device and external programmers or medical instruments of patients that enable professionals to make alterations to the settings, acquire diagnostic data, and be observant of the device functioning remotely. Abbott's Infinity DBS system.
6. Applies a patented directional ON/OFF antenna to give exact stimulation to patients suffering from movement disorders like Parkinson's disease.

7. CHALLENGES AND LIMITATIONS

1. Biomedical telemetry antennae typically run on fairly little power to avoid interference in the system and compliance with regulatory standards. As a consequence of this, they often have a small operating coverage area, which induces signal degradation so that data transfer is not achieved with the necessary quality. The operation of equipment may necessitate patients to be located in the proximity of receiving devices or monitoring points which mostly constrain mobility and flexibility.
2. The telemetry antennas for biomedical telemetry might be deterred by other electronic devices that are working in the same frequency degree, for instance, if we mention any of the WI-FI networks, cellular signals, or other medical devices. Interference in collaboration can result in an unstable signal that may lead to data loss or corruption which eventually may compromise the improvement of medical facilities.

3. Wireless data transmitting requires energy, hence biomedical telemetry antennae must be energy efficient rather than use batteries that cause batteries to release more radiation. Nevertheless, the matter of allocating powers and the competence of the antenna in terms of low-power operation may be a complicated task, with low performance and efficiency as a result.
4. In-body devices, like implantable cardiac and neuro-stimulators, must generate radio communication of an electromagnetic field being absolutely biocompatible to the human body and eliminating the possibility of unpredictable or undesired consequences and undesired effects on the tissue. The issue of biocompatibility without losing the antenna characteristics may be disposed of only through special materials and layerings used for the solar cell which will fit in the implant.
5. Usually, Biomedical telemetry is characterized by highly compact, small in size, and very light antennas. This is to enable the coating of such devices with patient-worn or implantable medical devices without causing discomfort or impeding patient mobility. Despite this, reducing the size of the antennae below the current size may impact the performance, for sure, especially including signal strength and frequency freedom. Designing antennas to match in terms of their size, performance, and form is a rather hard scaling balance.

8. HOW TO OVERCOME THE OBSTACLES

1. **Standards and Interoperability:** Develop and adhere to industry standards such as data formats, communication protocols, and connectivity interfaces to have total compatibility and integration with various medical equipment, systems, and devices. Engage all parties including the device manufacturers, software producers, health care providers, and regulatory officials to cooperate and build interoperability standards frameworks and common norms. Apply usability, safety, and efficacy tests in addition to certifying processes to check standard conformity and harmonized operation of healthcare engineering devices in different environments.
2. **Technological Advancements:** Increase funding to address technological obstacles such as range, power consumption, and signal interferences through the examination of novel antenna designs, signal processing techniques, and wireless technologies for communications. Use AI, ML, and edge computing to boost the efficiency, reliability, and security of biomedical telemetry devices, allowing data gathering in real-time, with detection of anomalies, and predictive maintenance activities. Use burgeoning technologies including blockchain and distributed ledger technology to enhance data quality, traceability, and auditicity thus decreasing the possibility of data tampering, illegal access, and breach.
3. **Regulatory and legal frameworks:** Collaborate with regulatory bodies as well as respective lawmakers to establish a specific and comprehensive legal framework for telemetry technology use in biomedical, assuring adherence to the state of patient rights in data privacy laws, devices safety standards, and so on. Create regulatory sandboxes or innovation hubs that would provide the opportunity for interaction and cooperation between industry and the regulators ensuring that the process is iterative permitting continuous enhancement of the regulatory frameworks towards improvement of the technology efficacy while preserving the interests of patients and the public health. Privacy protection factors, data access policies, and auditing trails should be incorporated to create data access rules and to assure regulatory compliance.
4. **Privacy and Data Security:** With security being one of the main concerns, be sure that transmission, storage, and processing of sensitive medical data are not compromised by using privacy-preserving technologies like secure multiparty computation, homomorphic encryption, and differential privacy. Apply privacy by designed principles and privacy impact assessments to examine and lessen privacy issues at the juvenile biomedical telemetry life-cycle at the onset of device design and deployment, data management, and disposal. Educate healthcare professionals, patients, and caregivers on their rights and duties regarding the privacy and security of their data and enable them to make wise and proactive choices for safeguarding their personal health information.

9. CONCLUSION

Besides the groundbreaking biomedical telemetry antennas capable of enabling a prompt tick-off in the real-time monitoring of medical devices and centralized systems, the healthcare system is on the verge of a revolution. In order to extend the coverage area, improve data rates, and reduce power efficiency, there has to be development of materials, fabrication methods, and some other types of antenna e.g., wearable and then implantable ones. Biomedical telemetry antennas are used in the healthcare industry for several different applications. Examples of these are the Internet of Medical Things (IoMT) and patient monitoring far from a doctor's office. This paper addresses the prospective practical scenarios of launching biomedical telemetry antennas in combination with breakthrough technologies such as edge computing, 5G, and AI. An evolving healthcare service monitoring application is because of the combination of the IoT and WBANs. With overcoming security and confidentiality challenges, the technologies gain new options for healthcare monitoring. We focus on the application of the patch antennas for connection through body/off body way, direct magnetic loop for noninvasive fracture monitoring, and the utilization of hybrid fractal antennas for different biomaterials. The study also highlights the need for rules, privacy, and ethical issues in these systems as it explores the possibilities of implanted sensors in biomedical technology.

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