Wearable and implantable antennas for healthcare applications: advancements, challenges, and future directions

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ABSTRACT

The rise of personalized and remote healthcare solutions has accelerated the demand for reliable wireless communication systems integrated into medical devices. Among these, wearable and implantable antennas play a crucial role by enabling the seamless exchange of data between in-body or on-body sensors and external monitoring equipment. These antennas are key components in systems designed for continuous health monitoring, early diagnosis, and patient rehabilitation. Unlike conventional antennas, those used in medical applications must function efficiently in close contact with or inside the human body, often under challenging conditions such as body movement, varying tissue properties, and limited space. As a result, the design and development of these antennas require careful consideration of factors like flexibility, biocompatibility, low power operation, and electromagnetic safety. This study reviews recent publications from 2017 onwards on wearable and implantable antennas. The material type, operating frequency band, and operational environment are considered for the design of the wearable and implantable antenna. To minimize loss, the research employed a high-thickness substrate, gold, and graphene material for the radiating patch in most of the design. This review presents a detailed overview of recent advancements in wearable and implantable antennas tailored for healthcare applications, highlights current design challenges, and outlines future research opportunities in this rapidly evolving field.

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1. INTRODUCTION

Recent progress in wireless communication has played a pivotal role in transforming healthcare delivery. As the focus shifts toward remote patient monitoring, real-time health assessment, and individualized treatment plans, there is a rising need for medical devices that can transmit physiological data with high reliability and efficiency. Recent antenna designs have demonstrated the ability to maintain high gain and efficiency, even when integrated into flexible, body-worn systems.

The design of wearable antenna in [1], introduced slot-based structures and ground plane modifications have been shown to significantly enhance bandwidth while preserving stable operation near the human body. These characteristics are essential for wearable biomedical devices operating within the industrial, scientific, and medical (ISM) band. The work in [2] have introduced wearable antennas utilizing designer localized surface plasmons (LSPs) to achieve compact, multiband performance. These structures enhance radiation efficiency and impedance matching through innovative multiple-input multiple-output

(MIMO)-based geometries. Such designs show strong potential for applications in wireless body sensor networks and healthcare monitoring. Active dual-band antennas integrated with internet of things (IoT)-based systems have been shown in [3] to effectively transmit health data such as heart rate and body temperature. By incorporating slot structures and positive-intrinsic-negative (PIN) diode switching, these antennas operate reliably across 2.4 GHz and 5.8 GHz bands. A compact, conformal ultra-wideband (UWB) compact coplanar waveguide (CPW) antenna has been developed in [4] for on-body applications, offering wide impedance bandwidth through design enhancements like L-shaped stubs and a shortened ground plane. Evaluated over multilayer tissue models, it supports multiple frequency bands used in wireless medical systems. Its structural flexibility, low specific absorption rate (SAR), and integration with circuit components demonstrate strong potential for wearable use. Smart textiles embedded with energy-harvesting elements have been demonstrated as a viable solution for powering IoT-based wearable sensors in e-healthcare [5]. A digitally embroidered, battery-free harvester design enables multi-directional energy capture with strong beam performance and compact form. A compact antenna backed by an artificial magnetic conductor (AMC) has been designed in [6] to improve radio-frequency identification (RFID) tag performance for on-body applications at ultra-high frequency (UHF) frequencies. The AMC structure enhances antenna gain and read range by isolating it from the body, while maintaining flexibility and biocompatibility. Its breathable substrate allows for epidermal integration, supporting health parameter monitoring directly on the skin. A hybrid wearable antenna based on Moore's fractal geometry and a rectangular loop has been developed in [7] for on-body biomedical diagnostics. The dual-band antenna supports key healthcare frequencies, offering wide bandwidth, high efficiency, and low SAR when tested on body phantoms. Its compact design and robust performance make it well-suited for data transmission in IoT-enabled health monitoring systems.

An AMC-backed antenna [8] was developed for a cardio-pulmonary stethoscope to enhance sensitivity in detecting pulmonary edema through improved signal transmission. By addressing detuning issues found in conventional patch antennas, the proposed design achieves higher front-to-back ratio and wider beamwidth. Testing with phantom models confirms substantial sensitivity gains, making it effective for remote cardiopulmonary monitoring. Wearable fabric antennas [9] placed on various body parts were used to study multichannel signal behavior during human motion, particularly in rehabilitation scenarios. Using an ultra-wideband-multi-input multi-output (UWB-MIMO) channel sounder, time-varying data across eight dynamic channels revealed how body movement affects antenna performance and signal propagation. These findings offer valuable insights for optimizing energy-efficient radio-frequency (RF) design and communication protocols in on-body networks. Flexible miniaturized antennas designed on Kapton substrates have been developed in [10] for radar-based ultrawideband breast cancer detection. These antennas maintain good impedance matching under curvature and body contact, enhancing suitability for wearable diagnostics. Incorporating reflectors with conformal antenna arrays significantly boosts electromagnetic wave penetration into breast tissue, improving imaging sensitivity. Study [11] introduces a wearable circular patch antenna capable of operating in both omni- and unidirectional modes with dual polarization. It is constructed on a single-layer felt-based dielectric substrate, offering a cost-effective and straightforward fabrication process. Soni *et al.* [12] introduce an antenna design for tumor detection, implemented on a flexible polyimide substrate. A human tissue model containing a tumor is developed, and various simulation analyses are performed with the tumor positioned both in front of and behind the antenna to evaluate its sensing capability. In study [13], the potential of a compact circular bow-tie slot wearable textile antenna for medical imaging applications is investigated. A dielectric breast phantom with inclusions of varying sizes and positions is employed to simulate early-stage malignant tumors and assess the antenna's detection capabilities.

The article [14] proposed a compact dual-antenna system operating in the 2.4 GHz ISM band for biotelemetry applications. Initially a miniaturized T-shaped resonator and shorting via was design and later was transformed to dual antenna system. In order to improve isolation between the two elements neutral line along with defected ground were employed. The proposed system achieves enhanced isolation (> -37 dB), making it suitable for implantable devices. With a low SAR, it meets health safety standards while supporting high-speed data transmission. A miniaturized implantable antenna operating in the 401–406 MHz medical implant communication band has been developed [15] with a compact footprint of 12×12×0.64 mm. The antenna is fabricated on bio-compatible material and insulated with a silicone coating for safety. Simulations and measurements in body phantoms confirm a 74 MHz bandwidth and low specific absorption rate, meeting safety standards. Implantable antennas for intelligent health monitoring systems are studied in [16], with a focus on the effects of human body parameters like permittivity and conductivity on antenna performance. Two types of capsule antennas isolated and surface types are compared, and an inner-layer dipole antenna is proposed to minimize transmission loss while maximizing received power. The design optimizes performance by adjusting the internal impedance. The design of implantable antennas for intelligent health monitoring systems [17] is analyzed through the electromagnetic near-field distribution in the human alimentary canal. The study investigates the impact of operating frequency, body conductivity, and organ placement on the antenna's electronic field distribution and transmission characteristics. Impedance matching and transmission efficiency across different organs are also compared. A quad-element MIMO antenna [18] is integrated within a head implant to enhance data rates and reduce multipath fading. With a validated channel capacity of 19.9 bps/Hz, this design significantly outperforms traditional single-antenna systems for implantable applications.

A compact dual-band circularly polarized implantable antenna [19] is designed for biomedical telemetry in IMDs. Using symmetric meandering slots and shorting pins, the antenna achieves miniaturization while maintaining right-hand circular polarization and stable performance across varied tissue types. Integrated within a biocompatible shell, it demonstrates safe SAR levels and reliable operation across both wireless medical telemetry service (WMTS) and ISM bands. A compact 3D cubic MIMO antenna [20] with circular polarization is proposed for implantable biotelemetry in the upper arm, operating. The antenna ensures polarization-insensitive communication and reliable performance even with body movement, achieving low SAR and high data rates. An ultracompact 1×2 implantable antenna array [21] is designed for telehealth monitoring on the IoT platform. Compared to a single antenna element, the array demonstrates significant improvements in gain, front-to-back ratio, and efficiency due to reduced cross-polarization. Validated through both simulations and phantom-based measurements, the antenna array offers enhanced directionality and energy efficiency for reliable biotelemetry. A compact differential integrated antenna [22] is developed for implantable medical devices. The antenna's performance is validated through simulations and measurements in realistic body phantoms, showing reliable impedance bandwidths and low far-field gains. SAR analysis confirms the antenna's suitability for safe biomedical telemetry and continuous health monitoring. A compact implantable antenna [23] integrated with a rectifier enables efficient dual-band wireless power transfer and data transmission. The antenna system, tested in realistic phantoms, achieves high RF–DC efficiency and safe SAR levels. Demonstrated communication up to 2 meters confirms the antenna's suitability for remote patient health monitoring. The design in [24] introduces a compact circular dual-band implantable antenna using via holes, ground slots, and a superstrate to achieve miniaturization. The design in [25] presents a miniaturized dual-element MedRadio MIMO antenna that employs a spiral radiator, a helical ground structure, and folded ground strips to widen bandwidth and improve isolation. A triple-band implantable antenna system in [26] further reduces size through meandered radiating paths, an open-ended ground slot, and a shorting pin, while its integration with microelectronics and sensors and its evaluated link budget support its use in varied in-body applications.

The rapid development of wearable and implantable antenna technologies is transforming healthcare by enabling continuous monitoring and communication for medical applications. These antennas, ranging from fractal-based wearable designs to ultra-compact implantable systems, have demonstrated improvements in bandwidth, gain, efficiency, and safety, particularly in meeting SAR regulations. They are now integral to body-centric wireless communication systems that support diagnostics, therapy, and long-term health monitoring. Innovations in material science, structural miniaturization, and system integration have further enhanced their performance, making them indispensable components of modern biomedical devices.

The following sections of this paper explore the essential aspects of this evolving field. Section 2 covers the critical design considerations for wearable and implantable antennas, including structural and material factors. Section 3 delves into the key evaluation metrics that determine their effectiveness and safety. Section 4 presents recent advances in reconfigurable antenna systems tailored to dynamic healthcare scenarios. Finally, section 5 summarizes the findings and outlines future research directions.

2. DESIGN ASPECTS OF WEARABLE AND IMPLANTABLE ANTENNAS

Recent research on wearable and implantable antennas has focused on improving flexibility, compactness, and performance near the human body. Key design strategies include using low-loss substrates, optimizing ground planes, and modifying antenna geometry to maintain impedance matching and bandwidth. Flexible materials and compact structures help ensure comfort and reliability. This section highlights essential design aspects based on these developments and presents the evolution of a proposed wideband antenna.

2.1. Role of conductive material

The material selected for the conductive elements of the antenna plays a critical role in determining its efficiency and functionality. It must ensure effective signal transmission and allow for adjustments to improve performance.

In wearable antenna systems, conductive materials form the core of both radiating elements and feedlines, enabling efficient signal transmission. There are various conducting material other than copper, that includes silver, AgNW/PDMS, Graphene and gold whose performance are studied in [27]. Performance tuning in [1] was achieved by introducing various slot geometries, including vertical incisions and inverted

"C" shapes, enhancing impedance alignment and bandwidth without significantly affecting radiation efficiency. The design in [2] incorporates a metal-insulator-metal configuration where a circular metal disk positioned at the feed tip strengthens electromagnetic coupling and minimizes signal return. A similar reliance on conductive pathways is seen in [3], where a microstrip-fed antenna integrates a PIN diode to allow frequency reconfiguration across ISM bands. In [4], the antenna structure features stacked, umbrella-shaped radiators using standard conductive materials, modeled with simplified assumptions such as treating the battery as a perfect conductor to evaluate electromagnetic interaction accurately. Textile-based designs in [5] use conductive threads embroidered onto fabric to create both the patch and ground plane, offering flexibility while maintaining acceptable efficiency. The AMC unit design in [6] employs patterned metallic geometries, such as comb-shaped structures, to tune sub-GHz performance and improve shielding near the human body. Antennas like the one in [7] use Moore's fractal shapes etched from conductive layers to create efficient current paths. Similarly, the antenna in [8] features conductive layouts optimized for microstrip-fed and loop-based configurations to maintain minimal signal loss. The dual-polarized wearable antenna in [10], used for breast cancer detection, uses copper traces to support orthogonal current induction, ensuring dual-axis polarization and stable operation. The conductive layer in [11] forms the radiating patch, enabling signal transmission and reception. Its geometry controls polarization and impedance, while maintaining flexibility for wearable use. The antenna in [12] employs copper as the conductive layer for both the inset-fed patch and ground plane, ensuring efficient current flow and stable radiation performance. The copper metallization forms the primary radiating surface, enabling reliable interaction with the flexible polyimide substrate. This conductive layer is essential for accurate sensing, supporting consistent field distribution when the antenna is placed near the human tissue model for tumor detection The antenna in [13] uses self-adhesive copper tape as the conductive layer, providing stable current flow across the bow-tie slot structure. Its flexibility allows the conductive material to conform smoothly to the denim substrate, supporting wearable operation.

Implantable antennas require precise design of conductive traces that are typically sealed within biocompatible layers to avoid direct tissue exposure while preserving electrical functionality. In [14], features such as slotted patches, shorting vias, and T-shaped resonators are included to reduce antenna size and tailor performance within the 2.4–2.48 GHz band. Additional structures like neutralization lines and defected ground planes help manage mutual interference in multi-element setups. The design in [15] adopts a meandered-line patch backed by a ground plane, using slots to extend the current path and a miniature coaxial feed for signal input. In [16], the dipole radiator can be positioned on the capsule's outer shell or embedded within, with external placement benefiting from direct interaction with bodily fluids for better matching and transmission. The immersed coaxial dipole antenna (ICDA) structure enhances this by surrounding the dipole in deionized water to minimize dielectric losses. Designs like [18] employ copper-based meandered radiators and central vias to limit surface wave propagation and enhance signal isolation in compact configurations. The antenna in [19] incorporates shorting pins and strategically placed slots on the ground plane to support circular polarization and broader bandwidth. In [20], copper strips and asymmetrical ground-plane cuts are used for both tuning and polarization control. Similarly, [21] utilizes copper to fabricate compact loop elements and shorting structures, ensuring strong signal propagation even in high-dielectric environments. In [22], conductive spiral and interdigital branches support differential feeding, encouraging radiation modes that limit interference. The spiral radiator in [23] is tuned for operation at 0.915 and 2.45 GHz by combining path elongation and slot-loading techniques with a coaxial feed, achieving effective impedance alignment across both bands. The antenna in [24] uses metal conductors primarily copper with a tin-coated finish to form the radiating patch, ground plane, and via connections. These conductive elements guide the current flow that enables dual-band operation and maintain stable performance when the antenna is implanted in tissue. The antenna in [25] uses metallic spiral and helix lines on the patch and ground to guide current efficiently, enabling miniaturization and wide impedance bandwidth. These conductive paths also maintain low mutual coupling in the dual-element MIMO configuration. The antenna [26] uses metallic traces for the serpentine radiating patch, shorting via, and coaxial feed to guide currents efficiently, achieving triple-band operation and miniaturization. Ground plane slots enhance impedance matching and create an extra resonance without altering patch current. Conductors for batteries and sensors ensure proper electrical connectivity throughout the implant Across both wearable and implantable antenna technologies, conductive materials play an essential role in shaping performance, controlling impedance, and supporting radiation behavior. Copper remains the standard due to its superior electrical properties, though alternatives like conductive textiles offer unique advantages in flexibility. Wearable designs focus on low-profile, reconfigurable structures that maintain performance despite movement and body proximity. Conversely, implantable systems demand biocompatibility, compactness, and precise tuning to operate efficiently within the complex dielectric environment of the human body. In both applications, the deliberate use of conductive materials, geometrical design, and structural optimization ensures that the antennas meet their performance goals while remaining functional in their respective settings.

2.2. Role of substrate material

The substrate is a key component in wearable antenna designs, influencing flexibility, size, and overall performance. The right substrate material helps achieve a balance between electrical efficiency and comfort during use. The substrate selection for wearable antennas plays a crucial role in determining flexibility, efficiency, and overall antenna performance. RT/duroid 5880, used in [1], offers a low dielectric constant (εr=2.22) and an extremely low loss tangent (tanδ=0.0009), enabling semi-flexible structures that conform well to the human body while maintaining broadband stability. Arlon AD 450, as seen in [2], provides a higher relative permittivity (εr=4.5) and a low loss tangent (tanδ=0.0035), facilitating improved impedance matching and the excitation of multiple resonant modes. Rogers Duroid RO3003™, adopted in [3], ensures low dielectric losses at 2.4 GHz and 5.8 GHz frequencies, thanks to its stable εr of 3 and low tanδ of 0.0013. Polyimide, chosen in [4], is notable for its exceptional flexibility, minimal thickness (0.05 mm), and biocompatibility, supporting layered integration of sensors without sacrificing comfort. Cotton fabric is explored in [5] for its ease of embroidery and measured dielectric properties (εr ≈ 1.6, tanδ ≈ 0.02), proving suitable for low-profile RF designs. A nanocomposite substrate, developed in [6], uses silicone rubber infused with $BaTiO_3$ to boost permittivity (εr ≈ 6.24) while retaining flexibility and bio-compatibility, with strict process control ensuring dielectric integrity. Rogers RT/Duroid 5880, again utilized in [7], is valued for its PTFE-based composite structure and high signal integrity in broadband systems. In [8], a hybrid substrate approach compares FR4 and Rogers 5880 for CPS and fractal antennas, respectively, showing that lower dielectric constants enhance frequency response and environmental stability. Kapton polyimide, examined in [8], is employed for breast-conformal antennas, balancing εr (3.5) and flexibility, with the use of a superstrate layer providing additional biocompatibility. These material choices underscore the importance of balancing dielectric performance with physical adaptability for effective wearable antenna deployment. The felt substrate [22] ensures flexibility and comfort for wearable applications. Its dielectric properties help maintain impedance matching and stable radiation performance. Additionally, its low cost and simple fabrication make it suitable for IoT devices. The polyimide antenna [12] uses a flexible, low-loss substrate (εr=3.5, loss tangent 0.001), enabling stable radiation and reliable tumor sensing on human tissue. The bow-tie antenna [13] on denim (εr=1.77, loss tangent 0.03034, 0.7 mm thick) provides comfortable wearable integration. In both designs, the substrate's flexibility and dielectric characteristics ensure consistent field distribution and effective antenna operation.

For implantable antennas, substrate selection emphasizes miniaturization, biocompatibility, and electrical isolation within the lossy human body. High-permittivity substrates such as Rogers RO3010 (εr=10.2, tanδ ≈ 0.002) are repeatedly employed in [14]–[16], offering significant size reduction and stable performance through increased effective permittivity. Silicone coatings with lower εr (≈2.1) complement these substrates by enhancing bio-compatibility and reducing tissue interaction. Substrate/superstrate combinations, such as those in [17] and [18], utilize thin dielectric layers to mitigate surface wave effects and provide mechanical robustness. Rogers RT/Duroid 6010, used in [19], offers a stable high-εr platform that enhances impedance matching and minimizes performance variation due to environmental dielectric shifts. Interestingly, study [20] adopts RT/Duroid 5880 (εr=2.2) for a cubic antenna configuration, leveraging low-loss attributes in combination with tissue-mimicking ATE phantoms for realistic modeling. In [21], Rogers RT/Duroid 3003 is selected for its balanced εr (3) and biocompatibility, suitable for resonance in the 2.45 GHz and 5.8 GHz ISM bands. High-dielectric materials like ceramic alumina (Al_2O_3, εr=9.8) are incorporated as superstrates or casings in [22] and [23] to enhance insulation and mechanical strength while supporting electrical performance and long-term implant safety. Collectively, these substrate systems ensure minimal electromagnetic loss, compact form factors, and safe operation within biological environments. Figure 1 tabulates substrate material, permittivity and advantages in wearable and implantable antenna design. The antenna in [24] uses Rogers 6010LM as its substrate and superstrate, a high-permittivity material that helps shrink the antenna size without sacrificing performance. Its low losses allow the antenna to operate efficiently even in the highly absorptive human tissue environment. By adding a superstrate layer, the design also minimizes detuning from tissue contact and helps maintain stable dual-band resonance. Rogers RT6010 is used as the substrate in [25], providing a high-permittivity platform that reduces antenna size while maintaining impedance performance. A thin biocompatible polyethylene layer prevents direct contact with the skin, stabilizing the antenna's resonance when implanted. Rogers RT/duriod 6010 provides mechanical support and stable resonance across all three bands, while enabling miniaturization [26]. Biocompatible ceramic alumina encases the device for safe implantation, protecting tissue from non-biocompatible substrate and electronic components.

Substrate material selection is pivotal in both wearable and implantable antenna designs, with each application presenting unique constraints. Wearable antennas prioritize flexibility, comfort, and mechanical resilience, thus favoring materials such as polyimide, cotton, and silicone composites that can conform to the human body while preserving electromagnetic integrity. In contrast, implantable antennas demand miniaturization, electrical isolation, and bio-compatibility, driving the use of high-permittivity materials like

Rogers RO3010 and ceramic alumina. Across both domains, a careful balance between dielectric performance, structural properties, and application-specific constraints governs substrate choice, ultimately influencing antenna size, efficiency, and operational reliability.

Figure 1. Substrate material used in wearable and implantable antennas

2.3. Fabrication techniques

The process of fabricating wearable antennas involves precision techniques to create the desired geometry and performance characteristics. These methods must accommodate both electrical and physical constraints to ensure reliable and efficient operation. The fabrication of wearable antennas, as seen in [1], adopts a systematic, multi-stage approach using standard printed circuit board (PCB) etching methods. The process begins with a basic rectangular patch and progresses through several stages of structural refinement, including the etching of vertical, elongated, and inverted "C" slots into the radiating patch to enhance impedance matching and bandwidth. Subsequent adjustments to the feedline involve introducing aperture slots that function as a stepped impedance transformer. Similarly, in [2], high-precision PCB fabrication is employed to realize periodic corrugated slots and a central metallic disk with a 0.5 mm air gap. Iterative simulation-based refinement leads to enhanced impedance matching and radiation performance, while standard SMA connectors and mounting provisions support practical deployment. The antenna in [3] is designed using CST Microwave Studio and fabricated with precision etching techniques. Design modifications, including an inverted U-slot and slotted ground plane, enable dual-band operation and wider bandwidth. A surface-mounted PIN diode and its biasing circuit are incorporated for active reconfigurability. In [4], a highly compact and integrated antenna system ($16\times10\times0.05$ mm^3) is built on a polyimide film using precision layering techniques. This includes stacked layers housing biosensors and electronic modules, with a coaxial feed for excitation. Performance is validated using a four-layer human tissue model. Digital embroidery is employed in [5] to fabricate a circular multiport rectenna array directly onto fabric. Each triangular patch element includes a compactly integrated voltage-doubling rectifier, and decoupling slots in the ground plane are used to reduce mutual coupling, achieving high isolation within a 24×24 cm^2 substrate. Additive manufacturing techniques, such as fused filament fabrication (FFF), are used in [6] to cast silicone-ceramic nanocomposite substrates, while conductive AMC patterns are added using screen printing.

Miniaturization is achieved through geometric modifications that extend the current path. In [7], fractal and loop geometries are patterned using precision etching, incorporating a partially grounded plane and embedded slots to enhance impedance and reduce back-lobe radiation. The Moore's fractal antenna applies a fourth-order Moore curve within a loop for compactness and matching. In [8], a square monopole is integrated with a 3×3 AMC array using a windmill and ring slot pattern for dual-resonance operation. AMC unit cell design evolves through geometric optimization to achieve broadband behavior. Lastly, study [10] details the design of CPW feed lines optimized for Kapton substrates. Both single- and dual-polarization antennas undergo geometric tuning to maintain |S11|< -10 dB across 2–4 GHz and ensure robust performance under variable anatomical conditions. The method in [11] employs a flexible felt substrate with conductive fabric on both sides, forming a compact and wearable antenna. The CAD-based pattern is laser-cut and adhered to the felt using eco-friendly double-sided tape. A 3 mm hole is drilled 8.5 mm off-center, and a 50 Ω SMA connector is soldered to complete the antenna. The antenna in [12] is fabricated on a flexible polyimide substrate, with copper metallization forming the inset-fed patch and ground plane. Standard microstrip fabrication methods are used to define the patch and slot geometry, optimized for tumor detection. Antenna in [13] is built on a denim textile substrate, with the conductive elements formed from self-adhesive copper tape. The tape is precisely cut using a laser cutter and bonded to both sides of the substrate, while a 3 mm through-hole accommodates the SMA connector. The fabrication approach uses eco-friendly adhesives and preserves the mechanical flexibility needed for comfortable wearable applications

Implantable antenna fabrication begins in [14] with a slotted patch design enhanced via T-shaped resonators and shorting vias to reduce resonant frequency and optimize impedance. Dual-antenna versions incorporate shared ground and decoupling methods, such as neutralization lines and defected ground structures (DGS), to suppress mutual coupling and improve isolation. In [15], the structure is refined by slot etching, extending the current path to achieve a resonance at 402 MHz with a return loss of −23 dB. Fabrication involves precision etching on R03010 substrates with silicone coatings, and simulations are conducted using CST and HFSS to validate SAR and gain within multi-layered tissue models. The design in [16] utilizes Rogers RO3010 substrate with coaxial feeding and integrates meandered lines and slots for miniaturization and frequency tuning. Biocompatibility is ensured with a silicone coating. In [18], semicircular meandered radiators and a metallic via are fabricated using multilayer PCB processes. Electromagnetic simulations and equivalent circuit modeling in Keysight ADS precede physical prototyping to ensure accuracy. Similarly, study [19] integrates centrosymmetric slot loading and metallic shorting elements to achieve miniaturization and dual-band performance, relying on multilayer alignment techniques typical of high-frequency biomedical antennas. The fabrication in [20] involves etching "S"-shaped meandered patches on multiple cube faces, using dry solid phantoms to emulate tissue properties. Variants from Ant-0 to Ant-3 are analyzed for circular polarization improvements. In [21], standard photolithography and PCB etching are used to print antenna elements on a substrate, which is then housed in a titanium enclosure (εr=43) to ensure biocompatibility. Precise spacing and element alignment are critical for internal performance. A more manual approach is followed in [22], where 3D printing and hand assembly form a cubic casing using ceramic alumina sheets and Styrofoam cavities for EM decoupling. Feeding ports are added for in-situ measurements. Finally, study [23] fabricates a multilayer antenna with spiral radiators, superstrates, and embedded slots. Coated with alumina for protection and biocompatibility, the antenna is tuned using etched slot patterns and shortened strips to achieve dual-band matching through careful control of inductive and capacitive parameters. The antenna is fabricated using Rogers 6010LM substrate material, which is cut and patterned to form the patch, ground plane, and via structures. A thin coating is applied to the conductive surfaces to prevent corrosion during implantation. The substrate and superstrate layers are then bonded using a light adhesive, ensuring structural integrity without affecting the antenna's electrical performance. The planar monopole antennas [25] are patterned on the Rogers RT6010 substrate with spiral radiators and helix ground lines. The dual-element MIMO system is realized by placing two elements close together, and a thin biocompatible coating is applied to prevent tissue contact, ensuring structural and electrical integrity. The serpentine patch [26], open-ended ground slot, and shorting via are patterned on the Rogers 6010 substrate. The coaxial feed is carefully positioned for impedance matching, and the entire device, including sensors and batteries, is encapsulated in ceramic alumina to ensure safe implantation Figure 2 gives summary of Fabrication Techniques used in Wearable and Implantable Antennas.

The fabrication techniques for wearable and implantable antennas demonstrate a diverse application of materials, structural innovations, and manufacturing methods tailored to each domain's specific constraints. Wearable antennas benefit from textile integration, additive manufacturing, and geometric miniaturization compatible with flexible substrates. In contrast, implantable antennas prioritize biocompatibility, miniaturization, and stable operation within the human body, relying on precise multilayer PCB methods and protective coatings. Across both domains, simulation-driven design iteration, careful substrate selection, and impedance tuning are central to achieving efficient, compact, and application-specific antenna systems.

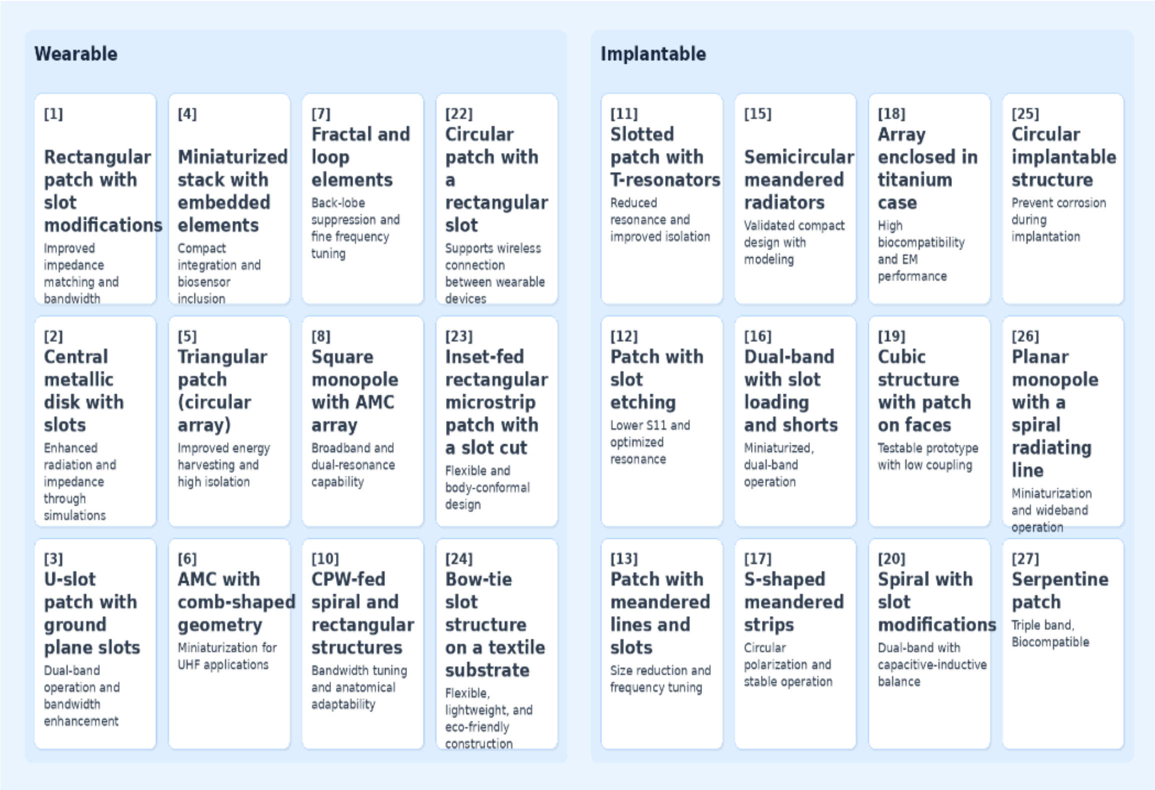

Figure 2. Summary of fabrication techniques in wearable and implantable antennas

2.4. Antenna structure

The antennas are engineered through step-by-step geometrical enhancements and integration with tuning elements, such as slots, shorting vias, or reconfigurable circuits, to meet specific performance targets including bandwidth, gain, impedance matching, and size constraints. Their evolution is often guided by simulation and iterative prototyping to ensure compatibility with wearable or implantable conditions, especially considering the effects of human tissue. This document categorizes and summarizes antenna design developments across twenty recent citations, divided into wearable and implantable categories, showcasing the progression in structural modifications and the corresponding performance improvements.

In [1], a five-stage antenna evolution (Ant-I to Ant-V) was presented, starting from a simple rectangular patch to incorporating an inverted "C"-shaped slot and feedline aperture slots, achieving resonance at 2.39 GHz with over 12% fractional bandwidth. Zhang *et al.* [2] described a staged design starting with poor impedance characteristics and ending with Fabry-Perot resonant behavior using MIM corrugations and a metallic disk. The antenna in [3] added an inverted U-shaped slot and a biasing circuit for frequency reconfigurability between 2.4 GHz and 5.8 GHz. Modak *et al.* [4] involved a six-stage evolution targeting UWB coverage (3.15–10.55 GHz), employing stacked umbrella patches and L-shaped stubs. In [5], equilateral triangular microstrip patches were arranged circularly for omnidirectional radiation at 2.45 GHz. The AMC design in [6] added comb-like protrusions to modify inductance and capacitance, resonating at 900 MHz and enabling antenna placement on AMC surfaces. Khan *et al.* [7] combined a Moore fractal and rectangular loop within a hybrid design, achieving miniaturization and enhanced impedance tuning. The CPS antenna in [8] evolved from a thin monopole to a square geometry on an AMC surface, offering dual-band performance and improved front-to-back ratio. Bahramiabarghouei *et al.* [10] tailored its design for breast cancer detection, progressing from a monopole to a dual-polarization spiral configuration, enhancing polarization sensitivity. This work integrated a staircase-shaped ground plane and spiral geometries to maintain performance over anatomical variations, ensuring consistent reflection coefficients. Figure 3 provides antennas structures of wearable antennas.

In [14], the antenna started as a slotted patch at 4.02 GHz and evolved to 2.4 GHz with T-resonators, shorting vias, and DGS to reduce coupling and increase gain. Soni *et al.* [12] transitioned from a basic patch to a compact 12×12×0.64 mm^3 structure resonating at 402 MHz, improving matching through slot etching. The antenna in [16] mirrored this evolution with slot integration and ground adjustment for in-body communications. In [18], a square patch transformed into a four-port MIMO system with meandered radiators, offering 32.6 dB isolation and 38.26% bandwidth at 433 MHz. Hu *et al.* [19] used centrosymmetric meandered slots and modified ground planes for circular polarization and enhanced radiation, suited for implants. The design in [20] introduced an "S"-shaped meandered strip and cube-based 3D MIMO architecture, enabling RHCP and LHCP across 2.45 and 5.8 GHz bands. Sharma *et al.* [21] began with a circular loop at 12 GHz, later tuning it to ISM bands using series loops, shorting strips, and forming a 1×2 array to enhance gain and FBR. The compact antenna in [22] featured a spiral patch and interdigital ground on a substrate, resonating at 915 MHz and validated across various tissue models. Lastly, study [23] described a four-step evolution involving multiple slot geometries, achieving dual-band performance at 0.915 and 2.45 GHz, with effective surface current distribution. Figure 4 provides antennas structures of implantable antennas.

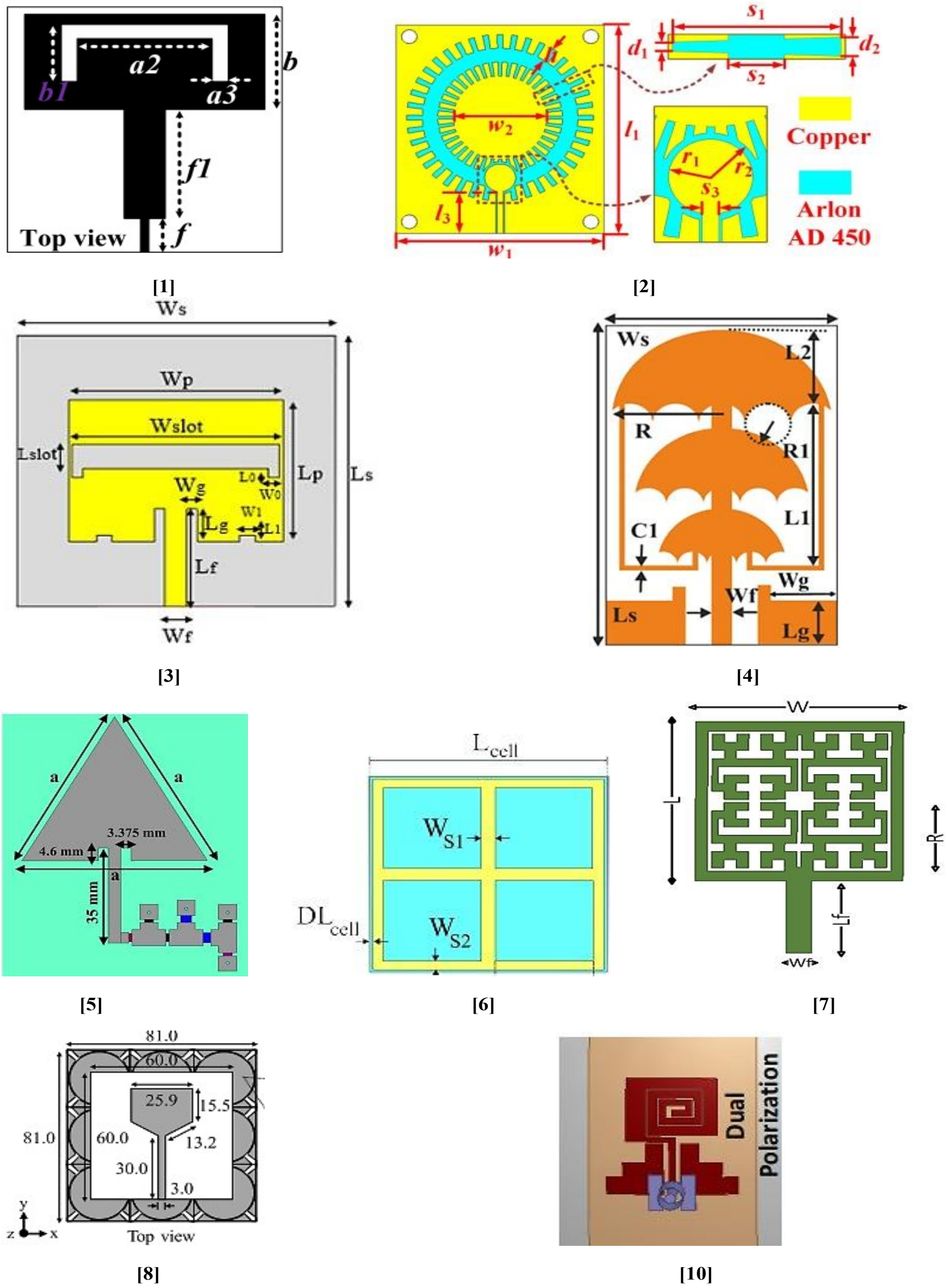

Figure 3. Reconfigurable wearable antenna structures in healthcare applications

The reviewed antenna designs exhibit diverse structural evolutions tailored for either wearable or implantable biomedical applications. Wearable antennas emphasize bandwidth expansion, polarization agility, and surface integration, while implantable designs focus on miniaturization, biocompatibility, and stable in-tissue operation. The iterative optimization and innovative structural adaptations demonstrated across citations [1]-[23] showcase significant strides in reconfigurable antenna technology. These advancements provide a robust foundation for future research, paving the way for more efficient, compact, and adaptive wireless communication systems in healthcare and IoT applications.

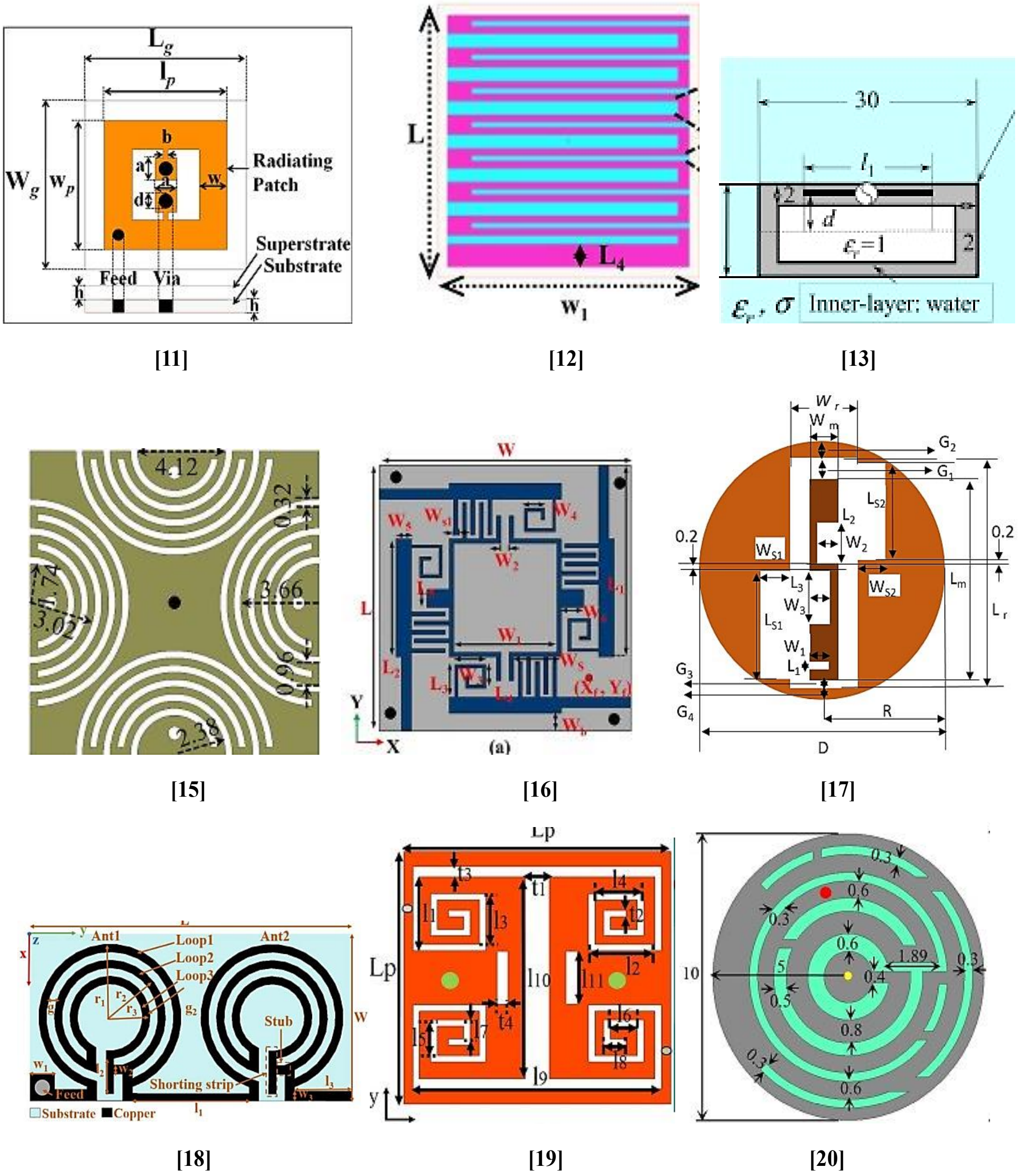

Figure 4. Reconfigurable implantable antenna structures in healthcare applications

2.5. Results and discussion

The medical sector will require wireless connection in the future generation of technologies. The antenna is one of the fundamental components that make this possible. Wearable and implantable antennas will be critical to achieving this. The paper focusses primarily on wearable antennas and implantable antennas. In the design of such an antenna, the conducting material and substrate material choices depending on the ISM and UWB bands are critical. Aside from these parameters, construction of the designed and simulated antenna is also critical. At times, the measured findings may disagree with the simulated results. Another essential factor is the constructed antenna, which must be taken into account when deployed in any wearable device or implanted. This includes operational bandwidth, efficiency, gain, and radiation pattern. Section 2.5.1 goes into detail about the parameter evaluation and the outcomes that come from it.

2.5.1. Evaluation parameters and results

A wide range of evaluation parameters such as bandwidth, gain, efficiency, impedance matching, SAR compliance, and miniaturization have been extensively explored in both wearable and implantable antennas to meet the rigorous demands of biomedical telemetry. These parameters are crucial for ensuring stable wireless communication, safe human-body interaction, and reliable data transfer. From substrate selection and structural optimization to testing in real-world body environments, the reviewed studies demonstrate consistent efforts to achieve high performance under compact, flexible, and biocompatible conditions. Both simulation and experimental validations were employed through the literature to confirm theoretical predictions and verify practical performance.

For wearable antennas, the emphasis lies in maintaining high radiation efficiency, wide bandwidth, and robust operation near or on the human body. For example, study [1] introduced a compact, flexible antenna with a peak gain of 3.67 dBi and 94% efficiency, operating in the 2.4 GHz ISM band with a 13.33% fractional bandwidth, retaining performance under bending conditions. Similarly, studies [2] and [3] demonstrated multiband and dual-band operation for body sensor networks and IoT-based healthcare using designs like annular slots and PIN diode switching, ensuring precise physiological measurements. Designs such as umbrella-shaped UWB antennas [4] and embroidered energy harvesting antennas [5] emphasized flexibility, compactness, and even battery-free operation, achieving conversion efficiencies up to 69%. The integration of artificial magnetic conductors and fractal geometries, as in [6]–[8], improved gain, read range, and minimized back radiation while keeping SAR within safe thresholds. Advanced implementations like a wearable breast imaging array [9] and bra-compatible sensors showcased medical-grade impedance matching and wave penetration, highlighting real-world deployment potential. The prototype in [11] was fabricated using laser-cut conductive textile layers bonded to a flexible felt substrate, ensuring a stable structure for reliable performance validation in both circular polarization (CP) and linear polarization (LP) modes. The antenna's performance [12] is assessed through parameters such as the reflection coefficient (S_{11}), 3D radiation patterns, directivity gain, and SAR values. These results confirm stable operation on the flexible substrate and demonstrate effective sensing capability when placed near the human tissue model. Evaluation in [13] includes simulated and measured S_{11}, radiation patterns at both operating bands, gain, and overall efficiency. The results show good agreement between simulation and measurement, validating the antenna's ability to detect small inclusions with reliable wearable performance.

Implantable antenna designs focused on miniaturization, biocompatibility, and deep-tissue performance without compromising SAR compliance. In study [14], a dual-antenna telemetry system achieved low mutual coupling (−37 dB) and stable transmission with just 280 mm^3 of volume. Abbas *et al.* [15] and Li *et al.* [16] explored medical implant communication service (MICS) band optimization and inner-layer capsule dipole configurations, balancing impedance matching and conductivity loss across various tissues. Studies such as [17] addressed how organ conductivity and internal contents influence signal attenuation, recommending diagnostic enhancements like stomach fluid manipulation. MIMO-based configurations [18], [20] introduced improved isolation and robust data rates even during body movement, whereas [19] ensured consistent dual-band circular polarization across body compositions. Ultra-compact arrays like in [21] achieved considerable gain and front-to-back ratio improvements, and differential implantable antennas [22] maintained performance under tissue variation and minor physical inconsistencies. The integrated wireless power transfer (WPT) system in [23] demonstrated practical wireless power delivery up to 2 meters with efficient energy conversion, verified through realistic tissue simulations. Figure 5 summarizes evaluation parameters considered for the antenna design and corresponding results. The antenna in [24] delivers stable dual-band performance with strong impedance matching in both simulated and real tissue environments. It also maintains safe SAR levels and consistent resonance, confirming its suitability for implantable biomedical use. The antenna in [25] achieves wide impedance bandwidth, with mutual coupling below –26 dB. The radiation efficiency is low due to lossy tissue. The antenna [26] resonates at 915, 1900, and 2450 MHz. Maximum SAR values comply with safety limits, and link budget analysis shows reliable communication up to 18 m, supporting high-data-rate applications.

Collectively, these findings reflect a continual evolution in antenna performance optimization tailored for biomedical applications. Wearable antennas achieving increased comfort and robustness through flexible substrates, slot structures, and miniaturized AMC layers, while implantable designs are advancing in complexity through multi-band operation, orientation-insensitive geometries, and power-autonomous solutions. These innovations, supported by comprehensive simulation and experimental data, validate their potential for deployment in next-generation healthcare monitoring, diagnostics, and real-time therapeutic systems.

Figure 5. Summary of antenna design parameters with results

3. CONCLUSION

In conclusion, wireless healthcare systems have evolved tremendously thanks to considerable developments in wearable and implanted antenna technology. These antennas address issues such as stringent miniaturization, mechanical deformation, and the requirement for biocompatible, low-power, and electromagnetically safe operation. Innovations include high permittivity substrates, flexible conductive composites, encapsulation in biocompatible coatings, and embedded matching structures have greatly increased radiation efficiency, SAR compliance, and structural durability. Moreover, developments in wireless power transfer and multiband communication are expanding medical equipment functionality for therapeutic, diagnostic, and continuing monitoring applications.

However, there are still considerable challenges to overcome. The key hurdles are assembling these components into tiny, patient-safe devices without losing longevity, providing effective far field communication across lossy tissue, and maintaining consistent antenna performance in the face of shifting physiological factors. The construction of reconfigurable designs and adaptive materials, more biocompatible packaging technologies, and standardized testing procedures that more closely resemble actual scenarios should be the focus of future research. The next generation of wearable technology and smart medical implants, which will create very reliable, minimally invasive tools for early diagnosis, real-time health tracking, and individualized care, will be made possible by resolving these problems. Wearable and implantable antennas are positioned to serve as the cornerstone of upcoming improvements in continuous and remote healthcare through interdisciplinary cooperation and innovation.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors

DATA AVAILABILITY

The data that support the findings of this study are openly available at reference number [1] to [27].

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