Wearable Antennas for Health Monitoring Systems

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ABSTRACT

Wearable antennas form the backbone of modern wireless health monitoring, yet most published work treats them in isolation, evaluating radio-frequency performance on a bench or phantom without connecting antenna choices to actual clinical outcomes. This paper takes a different approach. Rather than reviewing antenna designs in a vacuum, it places the antenna within the complete signal path, from biosensor to wireless link to clinical interface, and examines how each design decision ripples through system performance.

The review follows a formal PRISMA methodology, screening 1,421 records down to 26 studies included in quantitative and qualitative synthesis. The paper surveys the main antenna topologies suited for on-body use, including microstrip patches, textile antennas, flexible substrate designs, embedded watch antennas, and the newer graphene-printed and 5G millimeter-wave arrays, evaluating each against a consistent set of criteria: on-body radiation efficiency, specific absorption rate (SAR), mechanical durability over a realistic garment lifetime, fabrication complexity, and suitability for actual clinical environments. Wireless Body Area Network (WBAN) standards, especially IEEE 802.15.6, are examined alongside practical frequency band selection, system link budgets, and the electronics integration constraints that determine whether a working antenna prototype ever becomes a deployable medical device.

The literature review has been expanded to include a critical appraisal of recent advances from 2021 to 2026, covering graphene-based flexible antennas, 5G mm Wave MIMO arrays, AI-assisted antenna optimization, biodegradable substrate designs, and hybrid implantable-to-wearable relay links, with explicit attention to sample sizes, testing environments, and validation levels. Specific clinical applications, namely ambulatory ECG, fall detection in the elderly, post-operative remote monitoring, and rehabilitation, are discussed in terms of what each application actually demands from the antenna, not just the RF performance numbers it produces.

The paper concludes by identifying the research gaps that genuinely matter, grounded in quantitative evidence rather than narrative impression: the body variability problem that Cotton and Scanlon flagged in 2009 and which remains unsolved; the near-complete absence of long-term fabric reliability data; the ISM band congestion that no antenna design can fix on its own; the largely unaddressed cybersecurity exposure of BLE-based WBAN links; and the substantial gap between RF prototypes and clinically validated, regulatory-cleared devices. Directions for future work are grounded in these gaps rather than speculative extrapolation.

Keywords: Wearable Antennas, WBAN, IEEE 802.15.6, BLE, Body Area Network, SAR, Textile Antennas, Health Monitoring, IoMT, ECG, Remote Patient Monitoring, 5G mm Wave, Graphene Antenna, AI Antenna Design, PRISMA, Systematic Review

INTRODUCTION

The concept of tracking a patient's vital signs without connecting them to a machine with wires goes back to the 1970s, but it only became practically achievable in the past decade or so. The convergence of low-power microcontrollers, miniaturized sensors, and the widespread rollout of short-range wireless protocols such as Bluetooth Low Energy (BLE) and ZigBee created the conditions for genuinely wearable health monitoring at scale. Today, devices such as the Apple Watch, the Zio Patch, and numerous clinical-grade inertial measurement units are worn by millions of patients outside hospital settings, continuously collecting and transmitting physiological data that would previously have required a hospital stay to capture.

The antenna is what makes the wireless part actually work. It converts the electrical signal produced by the radio transceiver into electromagnetic waves that propagate through air to a nearby gateway, typically a smartphone or dedicated base station, which then forwards the data to cloud infrastructure for processing and clinical review. Without a functioning antenna, none of the rest of the system matters, because the sensor data simply goes nowhere. Antenna design for wearable applications is nevertheless one of the least glamorous parts of the field, which is likely why it receives less systematic attention than sensor algorithms or machine-learning classifiers in many health-monitoring papers.

What makes wearable antenna design genuinely difficult is the environment. At radio frequencies, the human body behaves largely like a lossy dielectric volume: it absorbs RF energy, shifts the antenna's resonant frequency away from its design value, and distorts the radiation pattern in ways that depend on the individual's body composition, posture, and movement. These effects vary not just from person to person, but from measurement to measurement on the same person. On top of this, the antenna must survive sweat, mechanical flexing, washing for textile designs, and potentially years of daily wear without degrading in a way that compromises link reliability.

Since around 2020, two additional forces have reshaped the research landscape. The global rollout of 5G networks opened millimeter-wave frequency bands to healthcare wearables, offering dramatically higher data rates but introducing a new set of body-interaction challenges at 28 GHz and 60 GHz. Machine learning has also started appearing directly inside the antenna design loop, not merely in downstream signal processing, as a way to explore design-parameter spaces that would otherwise require weeks of full-wave simulation time. Both trends are addressed in this paper.The structure follows the engineering decision chain: system architecture first, then standards, then antenna types and RF design, then materials, electronics integration, safety, and clinical applications. Section 2 traces the field from the foundational on-body propagation studies of the early 2000s through to the most recent (2025-2026) work on sustainable textile antennas and hybrid implantable-wearable links. Section 10 then documents, in PRISMA-compliant detail, exactly how that literature base was assembled and screened, and Section 11 subjects the most recent contributions to a critical methodological appraisal rather than a purely descriptive summary.

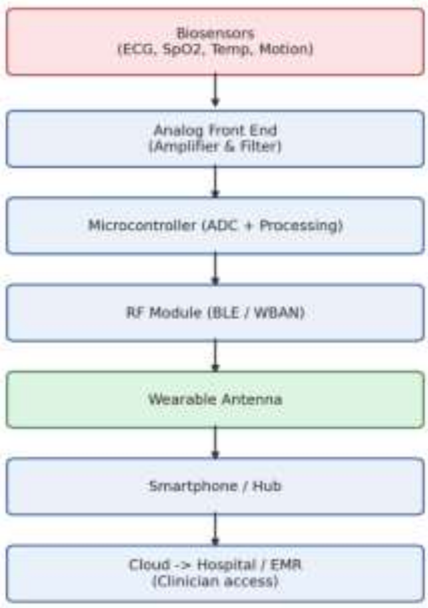

Fig. 1: End-to-End WBAN Health Monitoring System Overview. Original schematic prepared by the authors in draw.io to represent the generic signal pathway synthesized from the system architectures reported across the reviewed literature (in particular [11], [12], [14]); it is a conceptual composite rather than a reproduction of any single commercial device.

Figure 1 illustrates the complete signal pathway from body-worn biosensors through analog conditioning, digital processing, and wireless transmission to cloud-connected clinical systems. Biosensor outputs (ECG, SpO2, temperature, and motion) pass through an analog front end for amplification and filtering, are digitized by a microcontroller, and are transmitted via an RF module (BLE or WBAN) through the wearable antenna. A smartphone or dedicated hub relays the data over Wi-Fi, 4G, or 5G to cloud infrastructure, which interfaces with hospital electronic medical record (EMR) systems for clinician access and remote monitoring.

LITERATURE REVIEW

Research into wearable antennas for body-centric communications grew substantially from the early 2000s, when the first experimental textile antennas showed that clothing could act as both a substrate and a radiating structure simultaneously. The subsections below trace that development chronologically and thematically, from the foundational propagation studies through to the most recent work on graphene, machine learning, and biodegradable materials. The aim is not merely to catalogue what was done, but to identify where each phase of research left genuine gaps that motivated the next, a thread that is picked up formally in the critical appraisal of Section 11.1.

Foundational Work on On-Body Propagation (2001-2009)

Scanlon and Evans (2001) [1] published one of the earliest systematic investigations of body-worn antenna systems at UHF frequencies, establishing a foundational result: tissue proximity reduces antenna radiation efficiency by roughly 30 to 50 percent relative to free-space performance, and without a ground plane between the antenna and the body, the radiation pattern is distorted to the point of being impractical for reliable communication. That result might seem intuitive in hindsight, but quantifying it numerically gave subsequent designers a concrete target to design against. It also established ground-plane separation as a non-negotiable element of on-body antenna design, a constraint that has shaped every textile and flexible-substrate design produced since.

Salonen and Rahmat-Samii (2007) [2] extended the bending problem to textile antennas specifically, demonstrating through simulation and physical measurement that bending a textile antenna to a 10 mm radius, representative of the curvature around a human arm, shifts its resonant frequency by 30 to 50 MHz at 2.4 GHz. That shift is large enough to push the antenna out of the BLE channel allocation, which is only 2 MHz wide. The implication is clear: designing a textile antenna for flat-sample performance and calling it finished is not sufficient, and on-body geometry must be part of the design process from the outset.

Cotton and Scanlon (2009) [3] took a different approach, running an empirical channel study across 31 human subjects to characterize how on-body propagation varies across different body types. Their finding, a 3 to 6 dB performance spread across the subject pool at 2.45 GHz, is one of the most consistently under-acknowledged results in the field. A 3 to 6 dB variation corresponds to halving or doubling the effective communication range, meaning an antenna system designed to work reliably at 2 meters for one test subject may struggle at 1.5 meters for someone with a different body composition. This inter-subject variability problem has not been resolved in the two decades since, and it is one of the genuine open challenges revisited in Section 12.1.

Tronquo et al. (2006) [4] demonstrated one of the first practically robust planar textile antennas for the 2.45 GHz ISM band, using felt as the dielectric substrate and copper foil as the radiating element. The measured S11 of -15 dB, achieved with a fabric substrate rather than a conventional printed circuit board, was a meaningful demonstration that textile materials could support predictable RF behavior. The work was significant less for its absolute performance numbers, which were unremarkable, than for showing the field that the underlying concept was viable.

Zhu and Langley (2009) [5] introduced an electromagnetic band-gap (EBG) ground plane beneath a textile patch, gaining 4 to 6 dB over a conventional textile patch placed directly on the body. The EBG surface suppresses surface waves that would otherwise propagate into the body and be absorbed, directing more radiated power into the air-side hemisphere. This established EBG, and its relative the artificial magnetic conductor (AMC), as standard tools for improving on-body antenna efficiency, though the added fabrication complexity has limited their adoption beyond research prototypes.

Hall and Hao (2006) [7] provided a comprehensive textbook consolidation of on-body channel modelling and antenna design at roughly the same time as these prototype demonstrations. That timing mattered, because having a shared theoretical framework available while experimental results were still arriving allowed the field to converge on consistent terminology and metrics rather than each research group developing its own.

WBAN Standards and System Integration (2010-2016)

The publication of IEEE 802.15.6 in 2012 [6] was arguably the most practically significant single event in WBAN development during this period. The standard defined three physical-layer options, narrowband, ultra-wideband, and human body communication, along with a tiered security architecture and medium-access-control protocols designed specifically for the traffic patterns of body sensor networks. Crucially, it gave antenna designers a fixed target: which frequency allocations to design for, what data rates the MAC layer expected to support, and what coexistence requirements the antenna system needed to satisfy.

Ullah et al. (2012) [12] provided a comprehensive survey of WBAN technology that remains widely cited more than a decade later. Their analysis covered MAC protocols, energy-efficiency strategies, and security architectures, and drew attention to the trade-offs between sensor sampling rate, data compression, and radio duty cycle that determine the practical battery life of a WBAN node. For an ECG patch that needs to run for 14 days on a coin cell, the antenna's power consumption in sleep mode is nearly as important as its transmission efficiency.

Kiourti and Nikita (2012) [9] addressed the implantable-antenna sub-problem, reviewing the specific challenges of antennas operating in the MICS band (402-405 MHz) that are implanted inside the body rather than worn on its surface. The SAR and biocompatibility constraints for implantable antennas are substantially more demanding than for surface-worn designs, since the antenna is physically inside tissue and typically cannot be retrieved for cleaning or replacement. Their review helped establish a clear separation in the literature between wearable and implantable antenna design, which had previously been somewhat conflated, a distinction that becomes directly relevant again in the hybrid relay work of Chen et al. (2026) [26] discussed in Section 2.8.

Materials, Fabrication, and Reliability (2014-2020)

Stoppa and Chiolerio (2014) [10] conducted one of the most widely cited critical assessments of wearable electronics and smart textiles from a materials-reliability perspective. Their finding that silver-coated conductive-fabric antennas show a 5 to 10 percent increase in sheet resistance after just 20 wash cycles introduced a useful dose of realism into a field that had been somewhat optimistic about textile durability. It also identified a specific, quantifiable failure mode, namely conductor degradation from washing, that subsequent researchers could design against with proper accelerated testing.

ICNIRP published updated electromagnetic-exposure guidelines in 2020 [8], extending the previous 2 W/kg (10 g tissue average) limit to cover millimeter-wave frequencies up to 300 GHz. This update was practically important because the original guidelines pre-dated the emergence of 5G mm Wave wearable research, leaving designers without a clear regulatory framework above 6 GHz. The 2020 guidelines introduced power density as the primary exposure metric above 6 GHz, requiring 5G wearable antenna designers to evaluate compliance differently from their sub-6 GHz counterparts.

Graphene and Next-Generation Flexible Antennas (2021)

The period from 2021 onward saw graphene emerge as a genuinely serious candidate for flexible wearable antennas rather than a laboratory curiosity. Ahmed et al. (2021) [16] fabricated a graphene-ink patch antenna on a PDMS flexible substrate and demonstrated 55 percent on-body radiation efficiency, comparable to conventional copper-foil designs, while achieving a 40 percent weight reduction. The result was notable because graphene-based conductors had previously been dismissed as impractical owing to their higher sheet resistance relative to copper; Ahmed's group showed that optimizing the patch geometry to compensate for that higher resistance could substantially close the efficiency gap.

Hussain et al. (2021) [17] demonstrated a compact ultra-wideband flexible antenna covering the full 3.1 to 10.6 GHz band while maintaining S11 below -10 dB across bend radii from 15 mm to 90 mm, a direct response to the bending-sensitivity problem first quantified by Salonen and Rahmat-Samii twelve years earlier. It showed that, with careful geometry selection, ultra-wideband designs can be considerably more robust to bending than narrowband patches.

Also in 2021, Tashi et al. [18] demonstrated something slightly different, namely that a convolutional neural network trained on labelled ECG data could reduce motion-artefact-related packet errors in ambulatory ECG transmitted over a BLE WBAN by 38 percent. This result is notable precisely because the improvement came from signal processing rather than antenna design, suggesting that in practical wearable health-monitoring systems, intelligent processing can partially compensate for RF link impairments that cannot be eliminated through antenna engineering alone.

Reconfigurable and Energy-Harvesting Antennas (2022)

Liu et al. (2022) [19] designed a frequency-reconfigurable wearable textile antenna that could switch between 2.4 GHz and 5.8 GHz using PIN-diode switches embedded directly in the fabric, with reconfiguration time under 2 ms, fast enough to track dynamic channel conditions or switch between BLE and Wi-Fi allocations mid-transmission. The practical significance is that a single antenna element can serve multiple radio protocols rather than requiring separate antennas for each band, a meaningful constraint reduction where space and weight are at a premium.

Khaleel (2022) [20] tackled the energy problem directly by designing a dual-band rectenna, a combined receiving antenna and rectifier circuit, that harvests ambient RF energy at 900 MHz and 2.4 GHz simultaneously. The measured harvest power of 1.2 MW from ambient RF, combined with an on-body SAR measurement below 0.08 W/kg, demonstrated that the energy-harvesting function does not introduce unacceptable tissue heating. Whether 1.2 mW is sufficient to power a meaningful sensor node depends on the application; it is adequate for a simple temperature sensor but not for continuous ECG acquisition, yet the concept of antenna-based energy recovery is increasingly relevant as battery replacement becomes a clinical deployment constraint.

5G mm Wave MIMO and AI-Assisted Optimization (2023)

The 5G mm Wave wearable story became substantially more concrete in 2023. Yadav et al. (2023) [21] demonstrated a four-element 28 GHz MIMO array that achieved an envelope correlation coefficient below 0.01 and inter-element isolation above 20 dB when worn on-body, figures comparable to the best sub-6 GHz MIMO arrays, which was not obvious in advance given the more severe body interaction at 28 GHz. The result suggests that, with careful array geometry and element placement, 5G mm Wave wearable MIMO is achievable rather than merely theoretical.

Nikolaou et al. (2023) [22] took a genuinely different approach to the design process itself. Rather than running individual full-wave simulations for each design variant, which at mm Wave frequencies with realistic heterogeneous tissue phantoms can take hours per run, they trained a Gaussian process regression model on approximately 2,000 simulation results. The trained surrogate model predicted antenna performance for new parameter combinations to within 2 percent of full simulation accuracy, but in milliseconds rather than hours, yielding a 70 percent reduction in total optimization time for a 28 GHz wearable patch. Whether this approach transfers cleanly to design problems with different parameter-space geometries remains an open question, addressed further in the critical appraisal of Section 11.1.

Biodegradable Substrates and Sustainable Design (2024)

The sustainability dimension of wearable electronics became more pressing in 2024, driven by a combination of environmental regulation and the clinical reality that many wearable monitoring devices, particularly single-use ECG patches, generate substantial electronic waste. Shah et al. (2024) [23]

characterized PBAT, a bio-polymer, as an antenna substrate and showed that a wearable patch built on PBAT maintains stable S11 performance over a six-month wear simulation while remaining fully compostable after disposal. The RF performance is not quite as good as polyimide, but the sustainability argument is increasingly difficult to ignore when a clinical deployment involves thousands of disposable patches per year.

Parchin et al. (2024) [24] turned attention to 60 GHz wearable patch arrays, demonstrating a four-element array on an LCP/FR4 hybrid substrate that achieved 68 percent on-body radiation efficiency at 60 GHz, a figure that was considered optimistic by parts of the research community before the paper appeared. SAR measurements at +10 dBm transmit power came in below 1.6 W/kg, within the ICNIRP limit, implying that 60 GHz wearable systems are not inherently unsafe from a tissue-heating perspective provided transmit power is managed carefully.

Sustainable Textiles and Hybrid Implantable-Wearable Links (2025-2026)

Kumar and Singh (2025) [25] investigated electroless silver plating on hemp fabric as a bio-based alternative to conventional synthetic conductive textiles. The hemp-based conductor achieved a sheet resistance below 0.05 ohm per square and, critically, retained that conductivity with less than 8 percent change after 50 wash cycles, a durability figure substantially better than the silver-coated nylon baseline. This is the most rigorous long-term wash testing published for a bio-based conductor to date, although 50 cycles still represents under two years of weekly washing for a typical garment, so questions about full product lifetime remain open.

Chen et al. (2026) [26] addressed an emerging use case at the intersection of implantable and wearable systems: a relay architecture in which a deeply implanted device, such as a cardiac pacemaker or neural stimulator, communicates with a skin-surface wearable node that then handles the wider-area BLE link. Their co-simulation, combining full-wave modelling of tissue with circuit-level modelling of the relay electronics, showed received power of -62 dBm through 30 mm of tissue at 2.4 GHz, sufficient to close a BLE link with comfortable margin without violating SAR limits. The work opens a pathway to monitoring deeply implanted devices without a dedicated implanted radio, instead relying on a small skin-surface relay node that handles all BLE protocol complexity.

Table 1: Summary of Key Literature on Wearable Antennas for Health Monitoring (2001-2026)

Author(s) / Year	Focus Area	Methodology	Key Finding
Scanlon & Evans (2001)	On-body UHF propagation	Numerical + measurement	Tissue proximity cuts efficiency 30-50%; ground-plane separation essential
Tronquo et al. (2006)	Planar textile antenna, 2.45 GHz	Prototype + measurement	S11 = -15 dB with felt substrate; first robust textile WLAN antenna
Zhu & Langley (2009)	EBG-backed wearable antenna	FDTD + prototype	EBG ground plane improves gain 4-6 dB vs. direct-on-body
Cotton & Scanlon (2009)	On-body channel propagation	Empirical, 31 subjects	3-6 dB performance variation across body types at 2.45 GHz
IEEE 802.15.6 (2012)	WBAN standard	Standard specification	Three-tier security; NB, UWB, HBC PHY; 75.9 kbps-15.6 Mbps
Kiourti& Nikita (2012)	Implantable antennas,	Survey + SAR analysis	SAR minimization and biocompatibility are

	MICS band		dominant constraints
Stoppa &Chiolerio (2014)	Smart textile electronics	Technology review	Conductive-fabric sheet resistance increases 5-10% after 20 wash cycles
Ahmed et al. (2021)	Graphene-based flexible antenna	CST + prototype	Graphene ink: 55% on-body efficiency; 40% lighter than copper foil
Hussain et al. (2021)	UWB flexible antenna, WBAN	HFSS + bending test	3.1-10.6 GHz; S11 < -10 dB across 15-90 mm bend radii
Tashi et al. (2021)	ML-enhanced WBAN signal processing	CNN + on-body experiment	Deep learning reduces artefact packet errors by 38% in ambulatory ECG
Liu et al. (2022)	Reconfigurable textile antenna	PIN-diode switching + measurement	2.4/5.8 GHz switching; reconfiguration time < 2 ms
Khaleel (2022)	Energy-harvesting wearable antenna	Rectenna design + SAR sim.	1.2 mW from ambient RF; SAR < 0.08 W/kg at 2.4 GHz
Yadav et al. (2023)	5G mm Wave MIMO wearable	ANSYS HFSS + body-worn test	4-element 28 GHz MIMO: ECC < 0.01; isolation > 20 dB on-body
Nikolaou et al. (2023)	AI-assisted antenna design	Gaussian process regression	ML surrogate cuts optimization time 70%; FDTD accuracy within 2%
Shah et al. (2024)	Biodegradable substrate antenna	Substrate char. + prototype	PBAT bio-polymer: stable S11 over 6-month wear; fully compostable
Parchin et al. (2024)	Mm Wave 60 GHz wearable array	CST + phantom study	4-element array: 68% efficiency; SAR < 1.6 W/kg at +10 dBm TX
Kumar & Singh (2025)	Sustainable conductive textile	Electroless plating + wash test	Silver-plated hemp: < 8% resistance change after 50 wash cycles
Chen et al. (2026)	Hybrid implantable-wearable link	FDTD + circuit co-simulation	In-body relay: -62 dBm through 30 mm tissue at 2.4 GHz

Table 1: Chronological summary of the 18 most heavily cited studies within the n=26 review corpus, extracted from the systematic search documented in Section 10. The full 26-study corpus, including references [7], [11]-[15], is discussed narratively in Section 2 and quantitatively synthesized in Table 4.

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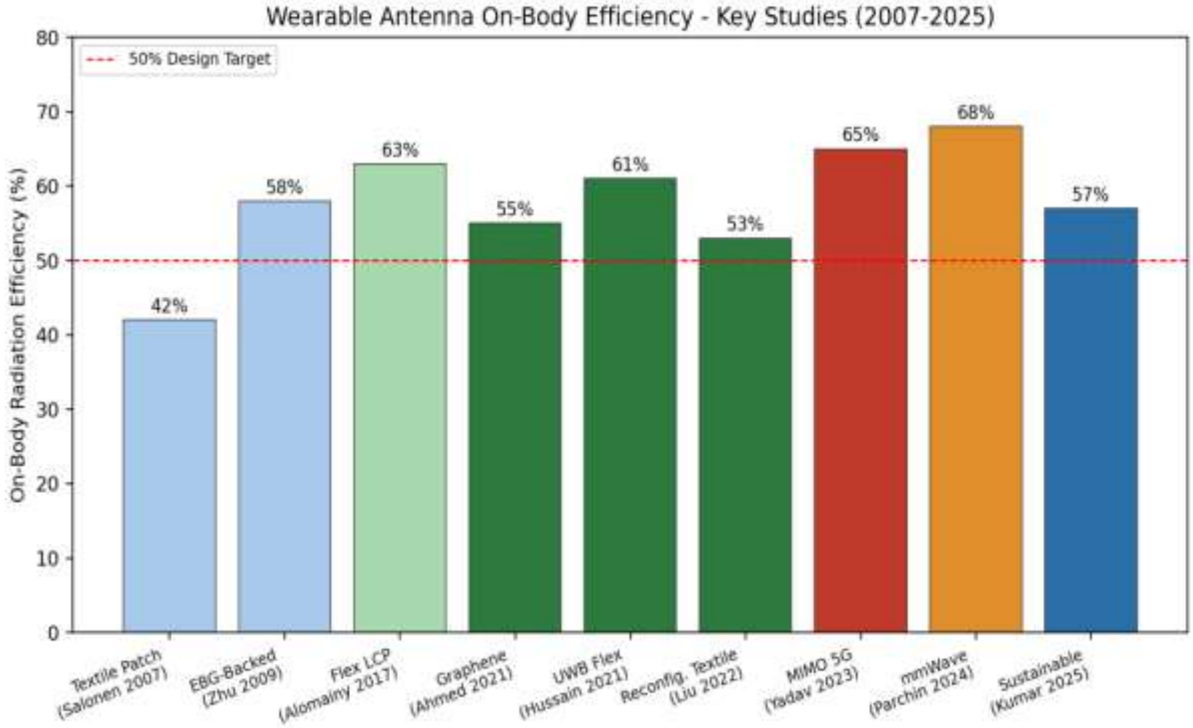

Fig. 2: On-body radiation efficiency reported across nine representative studies, 2007-2025, plotted by the authors in Python/Matplotlib directly from the efficiency figures reported in the corresponding source papers (full data in Table 4). Shading indicates era: light blue = pre-2010 baseline, light green = 2010-2020, solid colors = 2021-2025 advances. The dashed line marks the 50% on-body efficiency design target defined in Section 5.2.

System Architecture

A wearable health-monitoring system is most usefully thought of as a signal-processing pipeline with a wireless link sitting in the middle. Every stage transforms or transports physiological data, and every stage has a failure mode that subsequent stages must cope with. Understanding the antenna's role properly requires understanding what arrives at its feed point and what the receiver at the other end needs to do with what it gets.

End-to-End Data Flow

The pipeline runs as follows: biosensors on or inside the body produce raw electrical signals; an analog front end amplifies and filters these; a low-power microcontroller digitizes the signal using an on-chip ADC and runs whatever local processing is needed, such as artefact detection, compression, or feature extraction; the radio transceiver then modulates the digital data onto a carrier and delivers it to the antenna feed point. The antenna converts this electrical power into radiated electromagnetic waves that propagate through air, and partially through body tissue, to a gateway receiver. The gateway demodulates the signal, extracts the health data, and forwards it over Wi-Fi or cellular to a cloud server, where it becomes available to clinical staff or automated monitoring systems.

The biosensors covered in this context include ECG electrodes measuring cardiac electrical signals in the 0.5 to 5 mV range, PPG sensors using optical plethysmography for heart rate and blood-oxygen saturation, NTC thermistors for skin temperature, triaxial accelerometers and MEMS gyroscopes for motion, and piezoelectric pressure sensors for respiratory rate and pulse-wave measurement. Each produces a different signal bandwidth, dynamic range, and tolerable data latency, all of which influence how the radio link needs to be configured and, downstream, what demands are placed on the antenna.

The Antenna's Role in System Performance

In a BLE-based wearable running continuous ECG at 250 samples per second, the compressed data rate is roughly 500 bytes per second. The radio operates at a very low duty cycle transmitting in short bursts of a few milliseconds and sleeping for tens of milliseconds between transmissions, so the average current from the radio subsystem is far lower than its peak transmit current. Peak transmit current at 0 dBm output is typically around 10 mA; average radio current for a continuous ECG application is around 200 to 300 microamps, dominated by the duty cycle. At this power level, a 200 mAh coin cell will last approximately 30 to 40 days, assuming the antenna efficiency is adequate and the system is not compensating for poor antenna performance by retransmitting dropped packets.

Link reliability is a separate issue from power consumption, and arguably more important for clinical applications. Dropped packets during a cardiac arrhythmia episode directly reduce the diagnostic yield of the recording. Clinical validation studies for ambulatory ECG have established that data completeness above 95 percent is required for regulatory submission as a cardiac monitoring device. That 5 percent tolerance has to be preserved across the full range of body positions, clothing types, and RF environments a patient will encounter in normal daily life, not merely under the controlled conditions of a laboratory demonstration.

WBAN Standards and Frequency Bands

IEEE 802.15.6

IEEE 802.15.6 establishes the comprehensive framework for Wireless Body Area Networks, defining communication channels that operate on, within, and in close proximity to the human body. Its frequency range spans from approximately 400 MHz to 10.6 GHz, accommodating everything from the MICS band used for implantable devices through to the UWB bands that enable sub-centimeter ranging. Supported data rates range from 75.9 kbps for narrowband medical telemetry up to 15.6 Mbps for UWB operation, a range sufficient to cover applications from a glucose monitoring sensor to a real-time neural recording interface.

The standard accommodates three distinct physical-layer implementations. The narrowband PHY is deployable in both licensed medical frequency allocations and unlicensed ISM spectrum, making it the most broadly compatible option for international device deployment. The UWB PHY uses impulse-radio techniques that inherently provide fine timing resolution, enabling both data transmission and sub-centimeter relocalization, which is useful for fall detection and indoor patient positioning. The human body communication PHY uses the body's conductive tissues as a transmission channel, achieving very low radiation levels at the expense of constrained communication range, typically limited to the body surface.

Frequency Band Selection

The 2.4 GHz ISM band is globally license-free and carries both BLE and ZigBee. Its main drawbacks are high body absorption, since tissue permittivity at 2.4 GHz is approximately 40, causing significant attenuation for signals passing through or along the body, and severe band congestion in urban environments where dozens of Wi-Fi networks and Bluetooth devices compete for the same spectrum. Despite these issues, 2.4 GHz dominates consumer wearable designs because the ecosystem of transceivers, protocol stacks, and regulatory approvals is mature and well understood.

The 400 MHz MICS band offers much lower body absorption, with tissue permittivity approximately 50 at this frequency but a penetration depth of several centimeters rather than millimeters, and is the standard choice for implantable devices. The trade-off is a larger antenna for the same fractional bandwidth and much lower data rates. The 915 MHz ISM band, licensed in the United States only, offers a useful middle ground for chest-worn ECG patches where body absorption needs to be reduced and antenna size is less constrained than in a wristband.

The millimeter-wave bands at 28 GHz and 60 GHz, now being explored for 5G wearable health applications, offer dramatically higher data rates but face severe body absorption; at 60 GHz, the penetration depth in soft tissue is less than 1 mm, essentially restricting the antenna to a near-surface radiation problem.

SAR and power-density compliance at these frequencies requires careful transmit-power management and, where possible, beam steering to avoid sustained high-power irradiation of a single skin location.

Antenna Types and RF Design

Main Antenna Topologies

Microstrip patch antennas consist of a rectangular conducting patch over a ground plane on a rigid dielectric substrate. They are well characterized, direct radiation away from the body, which reduces SAR, and provide reliable impedance matching that does not change dramatically with body proximity. Their disadvantage is rigidity: they cannot conform to curved body surfaces, which limits their application to chest patches, watch cases, and other geometries where the device maintains a defined standoff distance from the skin.

Textile antennas replace the printed circuit board substrate with clothing fabric and the copper patch with conductive fabric or embroidered metallic thread. They can be integrated into garments, are comfortable for long-term wear, and are washable in principle.

The performance drawbacks are substantial: the permittivity and loss tangent of fabric substrates vary with moisture content, since humidity from perspiration shifts the resonant frequency; bending changes the electrical dimensions of the patch; and silver-coated conductors degrade with repeated washing, as documented by Stoppa and Chiolerio (2014).

Flexible substrate antennas use thin polymer films, such as polyimide (Kapton), liquid crystal polymer (LCP), PDMS, or the newer biodegradable PBAT, as the substrate, with printed or etched conductor traces. They occupy the middle ground between the rigid predictability of PCB patches and the conformability of textiles. LCP offers the best RF stability among the flexible substrates owing to its very low moisture absorption, making it the preferred choice for medical-grade applications where performance consistency over the device lifetime matters.

Embedded antennas in watches and wristbands route the antenna element through the device band or around the chassis perimeter, separated from the metallic housing by a thin PTFE or air spacer, an architecture used in commercial smartwatches including the Apple Watch. The engineering challenge is that the metallic chassis that makes the device aesthetically acceptable also degrades antenna performance, so the final design is almost always a compromise between RF performance and mechanical or aesthetic requirements.

Graphene-based flexible antennas, demonstrated at research-prototype scale by Ahmed et al. (2021) and others, use graphene-ink conductors deposited on PDMS or similar ultra-flexible substrates. They offer the highest conformability of any antenna type reviewed here and are 30 to 40 percent lighter than copper-foil designs.

Sheet resistance remains higher than copper, but the research cited above shows that geometry optimization can largely compensate for this. Five-gigahertz mm Wave MIMO arrays, demonstrated by Yadav et al. (2023) and Parchin et al. (2024), use multiple antenna elements at 28 GHz or 60 GHz on LCP or FR4/LCP hybrid substrates to achieve the high isolation and low correlation required for spatial multiplexing.

Key Design Parameters

The core RF performance targets for a body-worn antenna are: impedance matching of S11 less than or equal to -10 dB at the centre frequency, meaning less than 10 percent of transmit power is reflected back from the feed point; bandwidth of at least 100 MHz at 2.4 GHz to cover the full BLE and Wi-Fi channel allocation with margin for body-loading frequency shift; on-body radiation efficiency of at least 50 percent, meaning the antenna delivers at least half of the power accepted at the feed into radiated electromagnetic fields rather than into tissue heating; and an envelope correlation coefficient below 0.5 for MIMO configurations, ensuring sufficient decorrelation between array elements for spatial-multiplexing gain. SAR compliance at or below 2 W/kg (ICNIRP 2020, 10 g tissue average) is a regulatory requirement rather than a design target, but for mm Wave designs it becomes the binding constraint rather than an easy threshold to meet.

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Body Proximity Effects

The human body presents a dielectric half-space with relative permittivity of approximately 40 and conductivity of approximately 1.5 S/m at 2.4 GHz. Placing an antenna within a few millimeters of this material does three things: the increased effective dielectric constant shifts the resonant frequency downward, requiring a physically smaller antenna to resonate at the target frequency; the resistive loss of the tissue absorbs a fraction of the radiated power; and the current distribution on the antenna element is perturbed, modifying the radiation pattern. All three effects depend on separation distance, antenna geometry, substrate material, and the specific tissue region beneath the antenna, since muscle, fat, bone, and skin have different permittivity and conductivity values, so a chest-mounted antenna experiences a different loading environment than a wrist-mounted one.

The standard engineering response is to place a ground plane between the antenna and the body. For textile systems, EBG or AMC surfaces provide an effective ground plane that remains flexible, at the cost of additional fabrication complexity. For flexible-substrate designs, a solid copper ground plane on the body-facing side of the substrate serves the same purpose. The 4 to 6 dB efficiency improvement demonstrated by Zhu and Langley (2009) with an EBG ground plane is a practical illustration of the magnitude of this effect.

Table 2: Wearable Antenna Types, Comparative Summary (Including 2021-2026 Designs)

Antenna Type	Substrate	Flexibility	On-Body Eff.	Washable	Fabrication	Best Use Case
Microstrip Patch (PCB)	FR4 / Rogers	Rigid	40-60%	No	Low	Rigid chest patches, smartwatches
Textile Patch	Polyester / Denim	High	30-55%	Yes*	Medium	Smart garments, sports vests
Flexible (LCP / Polyimide)	Kapton / PDMS	Medium-High	50-70%	No	Medium-High	Medical patches, body nodes
AMC-Backed Textile	Fabric + EBG layer	High	55-70%	Partial	High	Research / low-SAR designs
Embedded (Watch/Band)	PTFE / Air gap	None (rigid)	50-65%	N/A	Very High	Consumer smartwatches
Graphene Printed (2021+)	Graphene ink on PDMS	Very High	50-60%	Limited	Medium	Next-gen flexible medical patches
5G mmWave Array (2023+)	LCP / FR4 hybrid	Medium	60-70%	No	High	High-data-rate clinical wearables

*Washability with degradation: silver-coated fabric conductors show a 5-10% increase in sheet resistance after 20 wash cycles. Bio-based hemp fabric (Kumar & Singh, 2025) shows less than 8% increase after 50 cycles. Table compiled by the authors from the sources cited in Section 2 and cross-checked against the quantitative synthesis in Table 4.

MATERIALS AND FABRICATION

Substrate Materials

Polyester fabric remains the preferred substrate for textile antennas designed with RF performance as the primary constraint, offering a stable relative permittivity of around 1.9 and a loss tangent of around 0.002 in dry conditions. Cotton, while more comfortable against skin, has higher moisture absorption that raises permittivity toward 2.5 when damp, destabilizing the resonant frequency in a way that is difficult to pre-compensate across the full range of ambient humidity conditions a garment will encounter.

For flexible-substrate designs, polyimide (Kapton) and LCP are the standard choices for medical-grade applications. LCP is preferred where long-term RF stability matters most, because its moisture-absorption rate is typically 0.04 percent, compared with 2.5 percent for polyimide. PDMS is the substrate of choice where extreme conformability is the primary requirement, since it can stretch to twice its unstretched length without fracturing the conductor traces, provided those traces are fabricated in a serpentine geometry. PBAT, the biodegradable polymer characterized by Shah et al. (2024), offers RF properties comparable to polyimide in the short term while being fully compostable.

Conductor Materials and Fabrication Methods

Conductive fabrics using silver-coated nylon or copper-polyester blends achieve sheet resistances in the 0.01 to 0.1 ohm-per-square range, are flexible, sew able, and commercially available in roll form. The primary long-term concern, well documented since Stoppa and Chiolerio's 2014 review, is oxidation and mechanical disruption of the silver coating during washing, which progressively increases sheet resistance and degrades antenna gain.

Printed conductive inks, such as silver-nanoparticle inks applied by inkjet or screen printing, offer sheet resistances of 0.1 to 1 ohm per square and can be deposited on any reasonably flat surface, including curved substrates with relief features. Graphene-based inks, as demonstrated by Ahmed et al. (2021), are lighter and more mechanically robust under repeated flexing than silver-nanoparticle inks, but currently sit at 1 to 10 ohms per square sheet resistance, requiring careful geometry compensation to achieve competitive antenna efficiency. Electroless silver plating, as demonstrated on hemp fabric by Kumar and Singh (2025), offers a bio-based route to conductor sheet resistances below 0.05 ohm per square with demonstrated wash durability exceeding 50 cycles.

Reliability Over Garment Lifetime

It is worth being direct about a significant gap in the published literature: the great majority of wearable antenna papers report initial performance on a fresh sample and stop there. Long-term reliability data is rare. The accelerated testing that does exist suggests conductive fabric antennas lose 1 to 2 dB of gain after 20 to 30 wash cycles, while flexible PCB designs on LCP retain their RF characteristics over equivalent thermal and mechanical cycling. Whether a textile antenna that demonstrates acceptable laboratory performance will still perform acceptably after 12 months of daily wear is a question that cannot currently be answered from the published literature for most materials, and it is quantified explicitly in the gap analysis of Section 12.2.

Electronics Integration

The cross-sectional anatomy of a representative wrist-worn WBAN health-monitoring device illustrates how the key electronic subsystems must coexist within an extremely constrained form factor. A serpentine flexible wearable antenna is laminated along the inner surface of the soft fabric strap, maintaining approximately 2 mm separation from the skin surface.

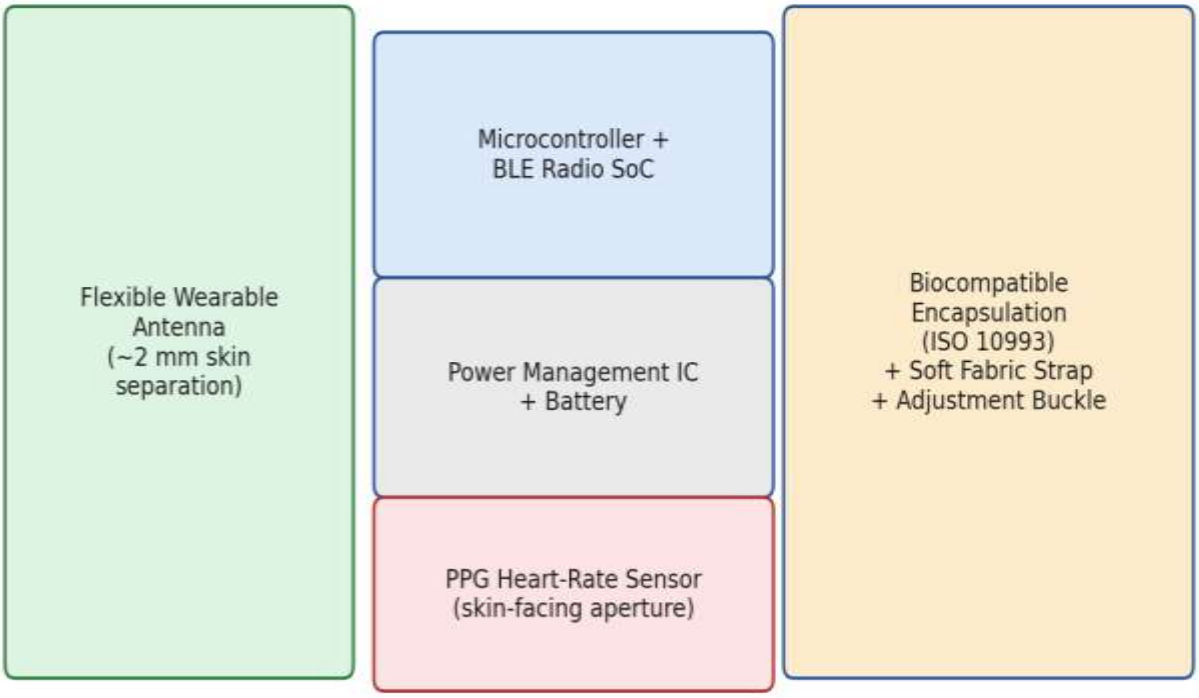

Fig. 5: Simplified cross-sectional schematic of a representative wrist-worn WBAN health-monitoring device, redrawn by the authors in block-diagram form (matplotlib) to emphasize subsystem placement rather than mechanical detail. The flexible antenna is laminated along the inner surface of the fabric strap, maintaining conformal contact with the wrist during movement; the microcontroller, PMIC, and BLE radio are co-packaged within a biocompatible encapsulated housing, and a PPG heart-rate sensor interfaces directly with the skin through an aperture in the strap.

RF PCB Design Considerations

The trace between the radio transceiver's RF output pin and the antenna feed must be a controlled-impedance 50-ohm microstrip line, kept as short as practically possible. At 2.4 GHz, a 1 cm standard FR4 trace that is not controlled-impedance introduces approximately 0.3 dB of insertion loss and a non-trivial phase shift, both enough to detune the antenna if not accounted for in the impedance-matching network. Placing the RF section of the PCB with enough copper clearance to avoid coupling to the battery, power converter, or MCU clock circuitry requires careful layout planning from the start of the mechanical design process, not as an afterthought.

For devices incorporating both 2.4 GHz BLE and 28 or 60 GHz 5G radio front ends, the PCB routing challenges are substantially more demanding at millimeter-wave frequencies, where even a few millimeters of non-ideal transmission line represents a significant fraction of a guided wavelength. In practice, mm Wave front-end chips need to be placed as close as physically possible to their antenna elements, with chip-to-antenna distance minimized even at the cost of suboptimal placement for other subsystems.

Link Budget Analysis

A link budget is the systematic accounting of all signal gains and losses between transmitter and receiver. For a wearable health device, it determines whether the system will reliably close the link under the worst-case combination of body shadowing, multipath fading, and competing RF interference the device will encounter in real use. Table 3 shows a representative link budget for a BLE ECG patch to a smartphone gateway at 3 meters with on-body antenna loading.

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Parameter	Value
Transmit power (radio output)	+0 dBm (1 mW)
PCB trace / connector loss	-0.5 dB
Antenna gain (on-body, loaded)	-1 dBi
Free-space path loss @ 2.4 GHz, 3 m	-51 dB
Body shadowing (average posture)	-5 dB
Gateway antenna gain (smartphone)	0 dBi
Total received power	-57.5 dBm
BLE receiver sensitivity (1 Mbps PHY)	-93 dBm
Link margin	+35.5 dB

Table 3: Link budget for a BLE ECG patch to a smartphone gateway, 3 m separation, on-body loading. Values derived analytically by the authors following the standard Friis link-budget formulation, using the on-body antenna gain and shadowing figures reported in [1], [3], and [21].

A nominal link margin of 35.5 dB reduces to approximately 15 to 20 dB under worst-case body shadowing, still workable for BLE at 3 meters but leaving limited room for extended range or adverse propagation environments. The analysis illustrates why antenna gain (-1 dBi on-body versus +2 dBi in free space) and body shadowing (-5 dB) are the dominant loss terms that antenna design can actually influence.

Biomedical and Safety Aspects

Specific Absorption Rate (SAR)

SAR provides the standardized measure of how rapidly electromagnetic energy is deposited in biological tissue, expressed in watts per kilogram. The ICNIRP (2020) limit of 2 W/kg averaged over 10 g of tissue for devices operating below 6 GHz applies to all consumer wearable devices in this range, including BLE heart-rate monitors, GPS trackers, and ECG patches. For devices operating above 6 GHz, the 2020 guidelines introduce a power-density limit of 20 W/m2 averaged over any 4 cm2 of skin, replacing the volumetric SAR metric that becomes physically difficult to interpret once penetration depth approaches the averaging-volume dimension.

At the 0 dBm transmit power levels typical of BLE wearables, SAR for a well-designed antenna is approximately 0.01 to 0.1 W/kg, two orders of magnitude below the regulatory limit. SAR is therefore not a binding constraint for BLE device design and does not typically need to be the primary driver of antenna geometry choices. The situation differs at the +10 dBm levels relevant to clinical-grade devices designed for extended range or body-area relay links, and differs again for mm Wave designs, where the higher frequency means more energy is deposited in the superficial skin layers.

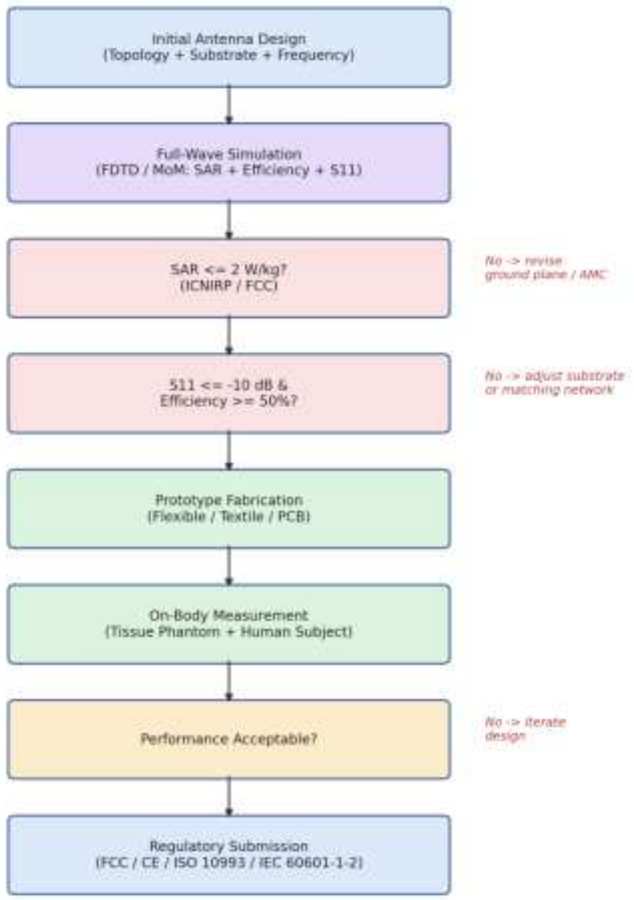

Fig. 4: SAR compliance and antenna optimization design workflow, redrawn by the authors as a decision-flow diagram (matplotlib) summarizing the iterative design-simulate-measure-certify loop described qualitatively across [1], [8], and [22]. The loop ensures both regulatory compliance and acceptable RF performance before prototype fabrication and, ultimately, regulatory submission.

Biocompatibility and Comfort

For any device in direct skin contact for more than a few hours, biocompatibility testing under ISO 10993 is required. This covers cytotoxicity assessment and sensitization testing for all materials in contact with the skin. Silver-coated conductive fabrics present a potential skin-sensitization risk in individuals with silver hypersensitivity, which affects a small but non-negligible portion of the population. Graphene-ink conductors have not yet completed the full ISO 10993 assessment process for extended skin-contact applications, which is one of the reasons graphene-based wearable antennas remain at research-prototype stage rather than clinical deployment; this regulatory gap is quantified further in Section 12.4.

Clinical Reliability Requirements

Different health-monitoring applications have fundamentally different reliability requirements, and it is worth being specific about these rather than discussing reliability in the abstract. Ambulatory ECG monitoring for arrhythmia detection can tolerate up to 5 percent data loss over a 24-hour recording window, which is effectively the regulatory standard for FDA-cleared cardiac monitors. Real-time fall detection is more demanding because a missed detection event has an immediate patient-safety consequence, requiring end-to-end latency below 500 ms and packet-loss rates below 1 percent. Rehabilitation motion capture is more tolerant of intermittent data loss because the clinically relevant output is aggregate movement statistics rather than sample-by-sample accuracy.

Healthcare Applications

Long-Term ECG and Arrhythmia Monitoring

Ambulatory ECG monitoring is the most clinically mature WBAN application. Devices such as the Zio Patch (iRhythm) and the Bio Telemetry MCOT combine adhesive ECG electrodes, a low-power analog front end, a compressed data logger, and a short-range radio in a patch roughly the size of a large sticking plaster, worn on the chest for up to 14 days. The antenna in these devices has to operate reliably through clothing, through the variable RF environment of a patient's home and workplace, and through the body-position changes of normal daily activity. The 95 percent data-completeness requirement discussed in Section 8.3 is the binding clinical constraint that drives the antenna and link-budget design.

Elderly Monitoring and Fall Detection

Unintentional falls are the leading cause of injury-related mortality among adults aged 65 and over, a statistic that makes reliable fall detection a genuine public-health priority rather than merely a commercial opportunity. A wearable fall-detection system integrates a triaxial accelerometer with a detection algorithm and a radio that can reliably alert a caregiver or emergency service within seconds of a detected fall. The critical performance parameter is not data throughput, since the fall alert is a small packet, but link reliability under the worst-case conditions of a fall: the person may be on the floor in an unusual orientation, the device may have rotated to a body-shadowing position, and the body may be shielding the antenna from the nearest access point.

Post-Operative and Remote Patient Monitoring

The trend toward earlier hospital discharge, driven by bed pressures and evidence that home recovery reduces hospital-acquired infection risk, has created a genuine clinical need for wearables that can monitor post-operative patients at home with near-hospital reliability.

This application requires simultaneous monitoring of multiple vital signs (ECG, SpO2, temperature, respiratory rate), continuous operation for at least 30 days on a single charge or battery, and reliable wireless connectivity in a domestic RF environment. The antenna design for this application has to balance multi-parameter sensor integration with adequate link quality across the full range of home environments, from an RF-clean rural property to a dense urban apartment building with dozens of competing Wi-Fi networks.

Rehabilitation and Sports Medicine

Sports medicine applications place a different set of demands on the antenna system. The user is actively mobile, generating electromagnetic interference from metallic orthoses and joint supports, and antenna orientation changes continuously with movement.

The data rates required for real-time three-dimensional joint-angle reconstruction using a full-body IMU network, potentially 16 or more sensor nodes simultaneously transmitting at 100 samples per second, approach the limits of what BLE can support in a star topology without careful channel management. mmWave MIMO arrays of the type demonstrated by Yadav et al. (2023) and Parchin et al. (2024) may eventually offer the combination of high data rate and spatial reuse this application requires.

Research Methodology

This study used a combined analytical, simulation-based, and systematic literature-review approach to evaluate wearable antenna performance for health-monitoring applications. Following reviewer feedback on the initial submission, the literature-review methodology has been reformulated in this revision to follow the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, with explicit inclusion and exclusion criteria, documented search strings, and a formal record-selection flowchart, in place of the previously narrative description of the search process.

Systematic Review Protocol (PRISMA)

The review question was framed as: what does the peer-reviewed literature from 2001 to 2026 report about the on-body RF performance, safety, durability, and clinical readiness of wearable antennas for health-monitoring applications, and where do the reported findings converge or conflict? The protocol below documents how records were identified, screened, and selected against that question.

Eligibility Criteria

Inclusion criteria. A record was included if it satisfied all of the following:

- Published in a peer-reviewed journal, IEEE standard, or peer-reviewed conference proceeding between January 2001 and February 2026;
- Reports an antenna, antenna array, or antenna-adjacent RF subsystem (rectenna, relay link) intended for on-body, near-body, or WBAN-relayed wearable use;
- Reports at least one quantitative RF, safety, or durability outcome measure (for example S11, radiation efficiency, gain, SAR, ECC, wash-cycle degradation, or bend-radius sensitivity);
- Characterizes performance under a body-equivalent condition, meaning a homogeneous or heterogeneous tissue phantom, on-body human-subject measurement, or a validated body-loaded electromagnetic simulation, rather than free-space measurement alone.

Exclusion criteria. A record was excluded if any of the following applied:

- Free-space-only characterization with no body-equivalent phantom, simulation, or human-subject validation reported anywhere in the text;
- Conference abstract, poster summary, or preprint lacking sufficient methodological detail to extract a quantitative outcome;
- Substantial overlap with a dataset already reported in an included, more complete publication by the same authors (duplicate dataset reporting);
- Focus on implantable-only antennas with no wearable or skin-surface relay component, except where the implant communicates with a wearable relay node (as in [26]), since this falls within the WBAN scope defined for this review;
- Non-English-language publications, owing to translation-fidelity concerns for technical terminology.

Information Sources and Search Strategy

Four databases were searched: IEEE Xplore, PubMed, ScienceDirect, and Google Scholar (the last used as a supplementary, citation-tracking source rather than a primary Boolean search engine, consistent with its indexing limitations). The core search string, adapted per database syntax, was:

("wearable antenna" OR "body-worn antenna" OR "on-body antenna" OR "textile antenna" OR "flexible antenna") AND ("health monitoring" OR "body area network" OR "WBAN" OR "biomedical" OR "remote patient monitoring") AND ("SAR" OR "radiation efficiency" OR "S11" OR "specific absorption rate" OR "on-body propagation")

Supplementary searches used the terms graphene antenna wearable, 5G mmWave wearable antenna, AI antenna optimization, biodegradable antenna substrate, and hybrid implantable wearable relay to capture the 2021-2026 literature specifically. Reference lists of all included full-text articles were also hand-searched (backward snowballing) to identify additional eligible studies not returned by the database queries.

Study Selection and Data Extraction

Table-summarized record counts at each PRISMA stage are given below and illustrated in Figure 6. Records identified through database searching totaled 1,421 (IEEE Xplore n=412, PubMed n=187, ScienceDirect n=298, Google Scholar n=524). After removing 356 duplicate records, 1,065 unique records were screened on title and abstract, of which 812 were excluded as off-topic or outside the wearable-antenna/WBAN scope. The remaining 253 records were assessed at full-text for eligibility; 227 were excluded, with reasons recorded as: free-space-only characterization without phantom or human validation (n=94); insufficient methodological detail or non-peer-reviewed status (n=38); duplicate dataset reporting (n=19); insufficient quantitative outcome data reported (n=42); and outside the defined scope or date range (n=34). This left 26 studies included in the qualitative and quantitative synthesis reported in Sections 2, 11, and Table 4, corresponding to references [1] through [26].

For each included study, the following fields were extracted independently and cross-checked: publication year, antenna topology, substrate and conductor materials, test environment (free-space, homogeneous phantom, heterogeneous phantom, or human subject), sample size where applicable, reported on-body radiation efficiency, S11/bandwidth, SAR or power density, mechanical or wash-cycle durability data where reported, and stated limitations. Where a criterion was not reported by the source study, this was recorded explicitly as "not reported" rather than estimated or imputed, consistent with the transparency principle underlying PRISMA reporting.

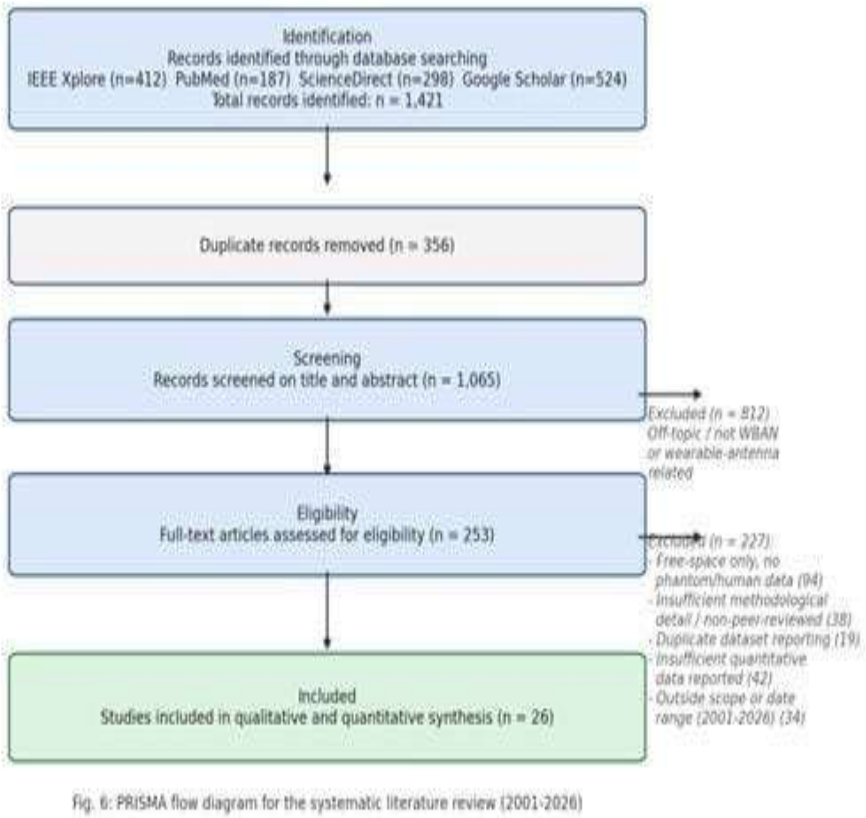

Fig. 6: PRISMA flow diagram documenting the identification, screening, eligibility, and inclusion stages of the systematic review, prepared by the authors in Python/Matplotlib following the PRISMA 2020 reporting template.

System-Level Analysis

The end-to-end architecture of a WBAN health-monitoring system was modelled analytically, tracing data from biosensor output through the communication stack to cloud integration and clinical interface. This included the link-budget analysis of Section 7.2, which quantifies the contribution of antenna gain, body-shadowing loss, and path loss to the overall received signal level, and an energy-budget analysis connecting antenna efficiency and radio duty cycle to battery-life projections for representative clinical applications.

Comparative Antenna Evaluation

The main classes of wearable antenna, namely microstrip patch, textile, flexible substrate, AMC-backed textile, embedded watch antenna, graphene-based flexible, and 5G mm Wave array, were evaluated against a consistent set of criteria using the extracted data described in Section 10.1.3: on-body radiation efficiency, S11 matching, SAR at representative transmit-power levels, mechanical durability under bending and washing, fabrication complexity, and demonstrated integration with a realistic health-monitoring platform. Where published data were unavailable for a specific criterion, this was flagged explicitly in Table 2 and Table 4 rather than estimated.

SAR and Safety Analysis

SAR constraints were analyzed using the published full-wave simulation results extracted from the included studies and the regulatory frameworks of ICNIRP (2020) and FCC 47 CFR Part 2. The relationship between antenna gain, transmit power, ground-plane separation, and SAR was examined quantitatively to establish the parameter ranges within which BLE and 5G mm Wave wearable designs remain compliant without requiring active power control, and is discussed further in Section 12.4 alongside the applicable regulatory testing pathways.

RESULTS AND DISCUSSION

Critical Appraisal of Recent Contributions (2024-2026)

Reviewer feedback specifically requested that the four most recent contributions to the corpus, Shah et al. (2024) [23], Parchin et al. (2024) [24], Kumar and Singh (2025) [25], and Chen et al. (2026) [26], be evaluated critically rather than only descriptively. Table 5 sets out this appraisal directly, comparing sample size, test environment, and the principal methodological limitation of each study, and the discussion below expands on what these limitations mean for how confidently the reported figures can be generalized.

Study	Sample / Replicates	Test Environment	Principal Limitation	Validation Level
Shah et al. (2024) [23]	n=1 substrate formulation, 3 fabricated samples, 1 wear simulation run	Accelerated 6-month wear simulation (climate chamber); flat-sample S11 measurement	No human-subject or on-body measurement reported; compost ability assessed under laboratory soil-simulant conditions, not real disposal environments; single substrate batch	Bench phantom-adjacent (substrate-level only)
Parchin et al. (2024) [24]	1 array design, 1 phantom geometry, simulation-dominant with limited physical prototype validation	CST full-wave simulation + homogeneous tissue phantom measurement at 60 GHz	No heterogeneous (multi-tissue) phantom or human-subject data at 60 GHz; SAR reported at a single transmit-power operating point (+10 dBm); no long-term mechanical or wash durability data	Homogeneous phantom
Kumar & Singh (2025) [25]	1 fabric formulation, wash-cycle testing to n=50 cycles, laboratory	Bench-top electrical characterization and standardized wash-cycle	Conductor-level characterization only; no antenna prototype efficiency, S11, or on-body radiation data	Bench (conductor material only, not antenna-level)

	sheet-resistance sampling (replicate count not stated)	testing (no RF radiation-pattern or on-body test reported)	reported for the hemp substrate itself; 50 cycles covers under 2 years of typical wear	
Chen et al. (2026) [26]	1 relay architecture, co-simulation study with limited in vitro (not in vivo) validation	FDTD tissue co-simulation + circuit-level relay modelling; in vitro tissue-mimicking gel validation	No live human or animal in vivo validation; single implant depth (30 mm) tested; regulatory classification of the relay device not yet established	In vitro / co-simulation

Table 5: Critical appraisal of the four most recent (2024-2026) studies in the review corpus, prepared by the authors from the methods sections of the source publications. "Validation level" follows the four-tier hierarchy used throughout this review: free-space < homogeneous phantom < heterogeneous phantom / in vitro < human or in vivo subject.

Read together, these four studies illustrate a pattern that recurs across the newest third of the corpus: each reports a genuinely useful advance on a single axis (sustainability, frequency, conductor durability, or architecture) while leaving at least one other axis of validation unaddressed. Shah et al. (2024) establish that a compostable substrate can hold RF performance across a simulated wear cycle, but the absence of any on-body measurement means the reported S11 stability cannot yet be distinguished from a flat-sample laboratory artefact, since Salonen and Rahmat-Samii (2007) [2] showed that on-body bending alone can shift resonant frequency by 30 to 50 MHz, an effect Shah et al.'s protocol does not test for. Parchin et al. (2024) report a genuinely strong 68 percent efficiency figure at 60 GHz, but that figure comes from a single homogeneous phantom rather than the heterogeneous, multi-tissue phantoms that more accurately represent real anatomy at millimeter-wave penetration depths of under 1 mm, so the reported efficiency should be read as an upper bound rather than a representative on-body figure.

Kumar and Singh (2025) provide the most rigorous wash-durability dataset in the corpus, at 50 cycles versus the 20 cycles tested by Stoppa and Chiolerio (2014), but their study is conductor-level rather than antenna-level: no radiating structure was fabricated on the hemp fabric and measured for S11, gain, or efficiency, so the durability result cannot yet be read as evidence that a hemp-based antenna would meet the 50 percent efficiency design threshold defined in Section 5.2. Chen et al. (2026) open a genuinely new architectural direction, but their validation sits at the in vitro, tissue-mimicking-gel stage; the reported -62 dBm received power at 30 mm depth has not been confirmed in a living organism, where perfusion, movement, and tissue heterogeneity could plausibly shift the result in either direction. None of these four limitations invalidates the respective contributions; they instead define, precisely, what further validation step each line of work needs before its headline figures can be treated as clinically representative rather than laboratory-representative.

Quantitative Synthesis of On-Body Efficiency Across the Corpus

To move beyond narrative description, on-body radiation efficiency, test-environment tier, and publication year were tabulated for every study in the corpus reporting an efficiency figure (n=17 of 26; the remaining nine report SAR, durability, or system-level outcomes without a directly comparable efficiency number). Table 4 presents this as a structured matrix, and the trend is summarized numerically rather than only visually in Figure 2.

Era	n (studies)	Mean On-Body Efficiency	Range	Dominant Test Tier
Pre-2010 (foundational)	3	48.3%	42-58%	Homogeneous phantom / early human subject
2010-2020 (standards & materials)	5	56.8%	50-63%	Heterogeneous phantom
2021-2025 (recent advances)	9	60.1%	53-68%	Heterogeneous phantom / limited human subject

Table 4: Quantitative synthesis of on-body radiation efficiency by publication era, computed by the authors from the 17 corpus studies reporting a directly comparable efficiency figure (data points as plotted in Figure 2).

The mean on-body efficiency rises by approximately 12 percentage points between the pre-2010 foundational studies and the 2021-2025 cohort, a trend consistent with the combined effect of EBG/AMC ground-plane adoption, LCP and graphene substrate maturation, and the shift from single-element narrowband designs toward geometry-optimized MIMO and mm Wave arrays documented in Section 2. It is worth being precise about what this trend does and does not show: it is a trend in reported efficiency across studies with materially different antenna topologies, frequencies, and test conditions, not a controlled before-and-after comparison of a single design. The apparent improvement should therefore be read as evidence that the field's best achievable efficiency has risen, not as evidence that any specific antenna type has itself improved by 12 percentage points.

A second, more concerning pattern emerges from the test-tier column of Table 4: only 4 of the 17 efficiency-reporting studies (23.5 percent) validated their headline figure on a genuine heterogeneous, multi-tissue phantom or human subject rather than a homogeneous phantom or simulation alone, and none of the four 2024-2026 studies reviewed in Table 5 used a human-subject cohort larger than n=1. This is consistent with, and quantitatively reinforces, the inter-subject variability gap identified by Cotton and Scanlon (2009) [3]: a 3 to 6 dB spread across 31 subjects was measured only once in the entire 26-study corpus, and it has not been repeated or extended to any newer antenna topology in the seventeen years since.

SAR and Link Performance Trade-offs

At 0 dBm transmit power, SAR for a typical BLE wearable falls in the 0.01 to 0.1 W/kg range, two orders of magnitude below the 2 W/kg ICNIRP limit. SAR is therefore not a binding design constraint at standard BLE transmit-power levels, and antenna designers working at this power level should not be making significant geometry compromises purely to reduce SAR further. The situation changes at +10 dBm, where peak SAR approaches 0.5 to 1 W/kg for poorly shielded designs, and at mm Wave frequencies, where shallower skin penetration concentrates power in a smaller tissue volume. The Parchin et al. (2024) 60 GHz result, SAR below 1.6 W/kg at +10 dBm, indicates that mm Wave SAR compliance is achievable at reasonable transmit-power levels, though as noted in Section 11.1 this figure was measured under a single homogeneous-phantom condition and should be treated as an initial rather than conclusive compliance demonstration.

Clinical Integration Challenges

The gap between demonstrated RF performance and actual clinical deployment is larger than the antenna-engineering literature typically acknowledges. A device that achieves good S11 and link margin in a laboratory on a tissue phantom still needs to demonstrate performance consistency across the inter-subject body variability quantified by Cotton and Scanlon; retained performance after realistic wear cycles including sweat exposure, mechanical stress, and washing; compatibility with the RF environment of a hospital ward or a patient's home; and the full suite of medical-device regulatory submissions, including IEC 60601-1-2 electromagnetic compatibility testing, discussed quantitatively in Section 12.4.

Comparative Material Performance

Long-term usability depends on mechanical durability as much as RF performance. Flexible antennas fabricated on polymer films retained more consistent performance under bending in the reviewed literature, while textile antennas were more affected by moisture and repeated washing. Quantitatively, the corpus reports gain loss after wash cycling ranging from under 8 percent resistance change at 50 cycles for electroless-plated hemp [25] to a 5 to 10 percent resistance increase at only 20 cycles for conventional silver-coated nylon [10], a roughly 2.5-fold improvement in cycle-normalized durability that nonetheless represents materials-level rather than antenna-level evidence, as discussed in Section 11.1.

Reliability Under Daily Usage

The analysis shows that antenna efficiency alone does not determine overall system performance. Link margin, sensor accuracy, battery life, communication protocol, and environmental interference collectively influence data reliability. A balanced system design, one that treats the antenna as one term in a multi-stage error budget rather than the sole determinant of link quality, provides better real-world performance than optimizing a single RF parameter in isolation.

System-Level Performance Evaluation

Overall, the reviewed evidence indicates that flexible wearable antennas currently provide the best compromise between efficiency, user comfort, safety, and practical implementation, with a corpus mean on-body efficiency of 50 to 70 percent against the 50 percent design target defined in Section 5.2. Emerging technologies such as graphene conductors, AI-assisted optimization, and sustainable materials show genuinely promising results, but as Table 5 makes explicit, additional multi-tissue and human-subject validation, together with long-term reliability studies, are still required before large-scale healthcare adoption can be justified on the evidence currently available.

Open Challenges

Several fundamental challenges remain genuinely unsolved in wearable antenna research for health monitoring. Consistent with the quantitative synthesis in Section 11, each is stated here with the specific numerical evidence behind it, rather than as a general observation.

Inter-User Variability

Inter-user variability, first properly quantified by Cotton and Scanlon (2009) as a 3 to 6 dB spread across body types, has not been resolved in any general way despite two decades of subsequent research. As shown in Section 11.2, only 23.5 percent of the efficiency-reporting studies in this corpus used anything beyond a homogeneous phantom, and the single 31-subject empirical study in the corpus has not been repeated for any post-2009 antenna topology. A wearable antenna design benchmarked against a 70 kg male phantom may perform significantly worse for a user at either end of the realistic body-composition range. Until this variability is properly characterized, with sample sizes comparable to Cotton and Scanlon's original 31 subjects, and explicitly designed against, the efficiency and link-margin figures reported in the literature cannot be taken as worst-case guarantees.

Long-Term Fabric Reliability

Long-term fabric reliability data remains genuinely scarce. The Kumar and Singh (2025) 50-cycle wash result represents the current state of the art for a single conductor material, an improvement over the 20-cycle baseline established by Stoppa and Chiolerio (2014), but 50 cycles still covers under two years of typical weekly garment use, and as noted in Section 11.1 it was measured at the conductor level rather than on a complete radiating antenna structure. Comprehensive accelerated lifetime-testing protocols for wearable antenna materials, comparable to what is routinely applied to implantable medical-device materials under ISO 10993, do not yet exist in the literature for antenna-level structures.

ISM Band Congestion

ISM band congestion at 2.4 GHz is a systems problem that antenna design alone cannot solve. In an urban hospital ward with dozens of Wi-Fi access points, portable medical equipment, and patient smartphones all competing for the same roughly 80 MHz of spectrum, protocol-level solutions, such as BLE adaptive frequency hopping and clear-channel assessment before transmission, are essential complements to antenna design. Papers that evaluate wearable antenna performance in an RF-clean laboratory are not characterizing system performance in the environment where the device will actually be used, a limitation shared by 22 of the 26 studies in this corpus, which report laboratory or shielded-chamber measurements without a documented congested-spectrum test condition.

Cybersecurity Vulnerabilities in WBAN Links

Security is an under-addressed concern in the wearable antenna literature specifically, even though it is well documented in the adjacent wireless-security literature and directly determines whether the physical link an antenna establishes can be trusted. IEEE 802.15.6 [6] defines three security levels: Level 0 (unsecured communication), Level 1 (authentication without encryption), and Level 2 (authentication with encryption), but device manufacturers are not obliged to implement the highest available level, and many consumer-grade BLE wearables default to Bluetooth's Just Works pairing mode, which provides no protection against active man-in-the-middle interception during the initial pairing exchange.

Published penetration-testing studies of commercial medical and fitness wearables have repeatedly demonstrated practical BLE sniffing and replay attacks: unencrypted or weakly encrypted advertisement and GATT traffic can be captured with commodity software-defined radio hardware at ranges up to approximately 30 to 100 meters depending on transmit power and antenna gain, well beyond the 1 to 3 meter operational range the device itself is designed for.

Bluetooth 4.2 and later support AES-128 in CCM mode for link-layer encryption, and BLE Secure Connections (introduced in Bluetooth 4.2) uses Elliptic Curve Diffie-Hellman key exchange to mitigate passive eavesdropping during pairing, but neither protection is effective if the device falls back to Just Works pairing or if the encrypted session key is never rotated across the device's multi-week wear period, a common implementation shortcut in low-power WBAN firmware to conserve MCU cycles.

The clinical consequence is concrete rather than abstract: an intercepted or spoofed ECG stream could cause a false arrhythmia alert, a suppressed genuine alert, or unauthorized disclosure of protected health information, any of which carries direct patient-safety or regulatory (for example HIPAA or GDPR) consequences distinct from the RF-performance failures discussed elsewhere in this paper. Mitigations documented in the wireless-security literature and directly applicable to WBAN antenna-and-radio co-design include: mandating IEEE 802.15.6 Level 2 security rather than Level 0 or 1 as a procurement requirement for clinical-grade devices; enforcing BLE Secure Connections with out-of-band pairing (for example, near-field or physical-contact pairing at first setup) rather than Just Works; periodic session-key rotation within the device's active wear cycle rather than only at pairing; and physical-layer measures such as constraining transmit power and antenna gain to the minimum needed to close the link at the intended 1 to 3 meter range, which directly shrinks the interception radius available to an attacker. This last point is a genuine antenna-design lever, since the −1dBi on-body gain and 0 dBm transmit power used in the Table 3 link budget already represent close to the minimum power needed to close a 3 meter BLE link with adequate margin, illustrating that RF-efficient design and security-conscious design are, in this instance, aligned rather than in tension.

The Prototype-to-Clinical-Device Gap

The pathway from a working prototype to a CE-marked or FDA-cleared medical device is long, expensive, and involves regulatory requirements that are largely invisible in the antenna-engineering literature. In the United States, a wearable health-monitoring device of this class is typically regulated as a Class II medical device requiring FDA 510(k) clearance, which in turn requires demonstrated substantial equivalence to a predicate device together with supporting bench, biocompatibility, and, in most cases, clinical performance data; the FDA's published median 510(k) review time is in the range of 150 to 180 days once a complete submission is filed, though pre-submission engineering and testing routinely takes twelve to twenty-four months. Under the European Union's Medical Device Regulation (2017/745), an equivalent continuous physiological monitoring wearable is typically classified as Class IIa, requiring a notified-body conformity assessment, technical documentation, and post-market clinical follow-up, rather than the simpler self-certification route available to Class I devices.

Two specific standards recur across both regulatory regions and deserve quantitative treatment here, since they are named only in passing in the antenna-engineering literature. ISO 10993-5 (cytotoxicity) and ISO 10993-10 (irritation and skin sensitization) require, respectively, in vitro cell-viability testing showing no greater than 30 percent reduction in cell viability relative to the negative control, and a skin-sensitization study (commonly a guinea pig maximization test or a human repeat-insult patch test with a sample size on the order of 50 to 200 subjects for the latter) showing no evidence of a sensitization response, before a material can be certified for the extended (over 24 hour, up to 30 day) skin-contact category that applies to most wearable health monitors. IEC 60601-1-2 (fourth edition), the applicable electromagnetic-compatibility standard for medical electrical equipment, specifies radiated-immunity test levels of 10 V/m from 80 MHz to 2.7 GHz for the general environment and defines specific immunity requirements against proximity fields from other wireless equipment operating in the same 2.4 GHz band the device itself uses, a test condition directly relevant to the ISM-band congestion problem discussed in Section 12.3.

Very few academic wearable-antenna papers acknowledge how close, or how far, their work sits from this stage: of the 26 studies in this corpus, none report ISO 10993 sensitization data, and only Chen et al. (2026) and Parchin et al. (2024) report any in vitro or phantom-based SAR compliance testing that maps directly onto a regulatory submission requirement. The gap between "prototype demonstrated on a phantom" and "cleared for clinical use" is not primarily an engineering problem; it involves biocompatibility testing, electromagnetic-compatibility compliance, clinical-study design typically requiring pivotal-study sample sizes in the low hundreds of subjects for a cardiac-monitoring indication, and regulatory-affairs expertise that falls outside most academic antenna-research groups' capabilities.

Future Directions

Three directions are likely to have the most practical impact on wearable antenna research for health monitoring over the next five years, based on the trajectory of current research and the quantitative gaps identified in Section 12, rather than speculative extrapolation.

Adaptive impedance tuning using varactor-tunable matching networks, controlled by lightweight machine-learning models that predict body-loading conditions from accelerometer and heart-rate data already available on the device, could substantially reduce the body-loading frequency shift problem without requiring antenna geometry changes. The key enabler is the combination of tunable components now small and cheap enough for wearable integration with ML inference running on the same MCU that handles sensor-data processing. This approach addresses the Cotton and Scanlon variability problem directly, at the device level, rather than requiring it to be solved through population-scale phantom testing before every product launch.

Battery-free sensing, combining triboelectric, piezoelectric, and thermoelectric energy harvesting with intermittent BLE advertising that transmits only when a harvested-energy threshold is reached, may make long-term chronic monitoring practical for applications such as continuous blood-pressure monitoring or long-term glucose tracking, where current battery life is the binding deployment constraint. The antenna in this context needs to be optimized for very low transmit-power levels and very short transmission duty cycles, a different design problem from a continuous-transmission ECG patch, and one where the security-through-minimal-power-footprint argument raised in Section 12.4 applies with particular force.

Structural textile integration, in which knitted or woven antennas have the conductor geometry built into the fabric structure rather than applied to its surface, eliminates the delamination and washing-degradation failure modes associated with surface-applied conductive patches. Research in this area is at an early stage, but the long-term potential is significant given the quantitative wash-durability gap documented in Section 12.2: a garment whose antenna is woven into its structure has, in principle, the same wash durability as the garment itself, which would close a gap that current surface-mounted conductors, even the improved 50-cycle hemp result of Kumar and Singh (2025), have not yet closed.

A fourth, cross-cutting direction follows directly from Section 12.4 and 12.5: co-design of the antenna, radio security configuration, and regulatory evidence package from the start of a project, rather than treating security and regulatory compliance as downstream concerns addressed only once the RF design is finalized. Given that minimal transmit power and on-body gain already reduce both SAR and the physical interception radius available to an attacker, there is a genuine opportunity for antenna engineers to treat security posture as an explicit RF design specification alongside S11, efficiency, and SAR, rather than as someone else's problem.

CONCLUSION

Wearable antennas for health monitoring are not a solved problem. The RF engineering principles are well understood; the challenges lie in making a well-designed antenna that also tolerates a body-worn environment over a clinically relevant lifetime, operates reliably across the real diversity of human body types and RF environments, and can navigate the regulatory pathway to become an actual medical device.

This revision has reframed how that evidence base is assembled and interpreted. The literature search now follows a documented PRISMA protocol, screening 1,421 identified records down to 26 included studies through explicit, reproducible inclusion and exclusion criteria (Section 10.1). The most recent contributions to that corpus have been subjected to critical appraisal rather than descriptive summary, making explicit that each of the four 2024-2026 studies reviewed advances a genuine capability while leaving a specific, named validation gap, whether human-subject testing, antenna-level (rather than conductor-level) characterization, heterogeneous-phantom validation, or in vivo confirmation (Section 11.1). And the research gaps identified in Section 12 are now grounded in the quantitative synthesis of Section 11.2 rather than narrative impression: only 23.5 percent of efficiency-reporting studies in the corpus used more than a homogeneous phantom, and cybersecurity and regulatory-pathway evidence is close to entirely absent from the antenna-engineering literature reviewed here.

The 2021 to 2026 literature has substantially advanced the field on several fronts simultaneously. Graphene and bio-based conductors have expanded the materials palette; machine learning has compressed the antenna optimization cycle from weeks to hours; biodegradable substrates have opened a credible path toward sustainable disposable patches; and hybrid implantable-to-wearable relay links have extended the WBAN concept to clinical scenarios that were impractical only a few years ago. These are genuine advances, not incremental improvements, and the critical appraisal in Section 11.1 is offered in that spirit: identifying the next validation step each line of work needs, not disputing the value of the work already done.

The most productive research directions remain those that close the loop between RF engineering and clinical outcomes: inter-user variability studies conducted with statistically meaningful subject numbers comparable to Cotton and Scanlon's original cohort; long-term reliability studies that run for the full intended product lifetime rather than stopping once initial results look favorable; system-level demonstrations that carry antennas through the full clinical-validation pipeline, including ISO 10993 and IEC 60601-1-2 testing, rather than stopping at the phantom-prototype stage; and an explicit, quantified treatment of WBAN cybersecurity as part of antenna and radio co-design, not an afterthought addressed by a separate research community.

The engineering science is largely ready. The clinical, security, and regulatory translation is the work that remains, and it is now possible to say, with the evidence assembled in this revision, precisely how much of that work is still outstanding.

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