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6G-Enabled Intelligent Healthcare: Technologies, Challenges, and Transformative Applications

Aniket Patel
Associate Professor & Head, Department of Computer Science and Engineering,
ICT, Faculty of Engineering and Technology, Ganpat University, Gujarat, 384012, India

Bhavesh Chavda
Research Scholar, Faculty of Engineering and Technology,
Ganpat University, Gujarat, 384012, India

Rohit Patel
Professor, ICT, Faculty of Engineering and Technology,
Ganpat University, Gujarat, 384012, India

Abstract

Sixth-generation (6G) wireless networks are poised to fundamentally transform healthcare delivery by enabling ultra-reliable, low-latency, and AI-native communication at an unprecedented scale. Key 6G enablers — terahertz (THz) communication, massive ultra-reliable low-latency communication (mURLLC), reconfigurable intelligent surfaces (RIS), edge intelligence, and blockchain-based data governance — collectively address persistent limitations of current 4G/5G medical infrastructures. This paper presents a structured analysis of 6G-enabled intelligent healthcare, synthesizing recent literature on smart hospitals, mobile health (m-health), the Internet of Medical Things (IoMT), and blockchain-driven electronic health records (EHR) (Patel et al., 2025; Anonna et al., 2026; Wang et al., 2026). Building on this synthesis, we propose a novel five-layer architectural reference model for 6G healthcare ecosystems, introduce a qualitative performance comparison framework benchmarking 6G against 4G and 5G across six clinical metrics, and provide a structured research gap taxonomy with actionable future directions. Key findings demonstrate that 6G can theoretically reduce clinical response latency from tens of milliseconds (5G) to below 1 ms, support device densities exceeding 10 million nodes per km², and enable secure, patient-controlled EHR sharing at scale. The paper further identifies unresolved challenges in THz propagation within hospital environments, deterministic URLLC verification, IoMT interoperability, explainable AI governance, and regulatory frameworks for autonomous clinical systems. By integrating technical, architectural, and socio-ethical perspectives, this paper delivers a comprehensive foundation for researchers, engineers, and policymakers advancing next-generation intelligent healthcare infrastructure.

Keywords: PVDF, FDM, Additive Manufacturing, AM, Expert system in AM

1. Introduction

The convergence of digital sensing, artificial intelligence, and wireless communications has driven substantial advances in healthcare over the past

Corresponding Author E-mail Address
arp02@ganpatuniversity.ac.in

decade. Despite the progress enabled by 4G and early 5G deployments, contemporary medical infrastructures continue to face fundamental constraints in latency, reliability, scalability, and secure data management (Tao & Zhang, 2022). Mission-critical services such as real-time telesurgery, continuous remote patient monitoring, autonomous medical robotics, and high-density IoMT ecosystems impose requirements that existing networks cannot consistently satisfy (Nguyen et al., 2022).

Sixth-generation (6G) wireless systems, anticipated for commercial deployment around 2030, represent a qualitative leap beyond 5G. By integrating terahertz (THz) communication, sub-millisecond latency, massive URLLC, AI-native network management, and reconfigurable intelligent surfaces, 6G establishes the communication substrate necessary for fully autonomous, context-aware, and real-time medical systems. Projections suggest that 6G will support data rates exceeding 1 Tbps, end-to-end latency below 0.1 ms, and device densities of 10^7 connections per km^2 — specifications that unlock healthcare applications currently beyond reach (Dang et al., 2020).

Simultaneously, the rapid growth of medical multimedia — including diagnostic imaging, holographic communication, and extended reality (XR) — demands quality-of-experience (QoE)-driven network optimization that 5G cannot adequately provide. Emerging 6G capabilities, combined with blockchain-based EHR governance, federated learning, and digital twin frameworks Ning et al. (2023), offer a path toward intelligent, equitable, and secure healthcare delivery at global scale (Chen et al., 2020; Hossain & Muhammad, 2019; Luo et al., 2026).

This paper makes the following primary contributions: (1) a critical synthesis of 6G enabling technologies and their specific relevance to clinical use cases; (2) a proposed five-layer reference architecture for 6G-enabled intelligent healthcare ecosystems; (3) a qualitative comparative performance framework benchmarking 6G against 4G and 5G across six clinical metrics; (4) a structured taxonomy of current research gaps with actionable directions; and (5) an end-to-end clinical workflow scenario demonstrating cross-layer system integration.

2. Background and Related Work

The trajectory of intelligent healthcare has been shaped by successive generations of wireless technology, each removing specific barriers while revealing new limitations. Early smart hospital deployments relied on IoT-cloud architectures that enabled remote monitoring and diagnostic support, but suffered from unacceptable latency (typically 30–100 ms), limited device concurrency, and insufficient bandwidth for medical multimedia. Comprehensive surveys confirm that even advanced 5G deployments cannot reliably support emerging healthcare requirements, particularly for high-density IoMT and real-time multimedia applications (You et al., 2020; Zhang et al., 2024; Wang et al., 2023; Anonna et al., 2026).

The potential of 6G for healthcare is increasingly recognized in the literature. Studies on 6G-enabled smart hospitals highlight superior device interoperability, ultra-reliable communications, and real-time clinical decision support (Taleb et al., 2020). Research on 6G-IoT convergence demonstrates how THz links, edge intelligence, space-air-ground integrated (SAGU) networks, and blockchain mechanisms can enhance IoMT functionality and enable autonomous health practices (Al-Turjman & Abujubbeh, 2019). Visionary analyses project that 6G will enable intelligent wearables, hospital-to-home (H2H) care models, and immersive telemedicine as mainstream modalities (Adeel et al., 2022). Blockchain-based EHR research further addresses data privacy and cross-institutional interoperability as foundational requirements for patient-centred data governance in hyperconnected networks.

Despite this body of work, significant gaps remain. Existing literature provides strong conceptual frameworks, but lacks: (a) validated architectural blueprints with cross-layer integration specifications, (b) quantitative comparisons of 6G versus prior generations on clinical performance metrics, (c) practical deployment guidelines for heterogeneous hospital environments, and (d) rigorous treatment of ethical AI

governance and regulatory certification for autonomous clinical systems. Table 1 positions this paper relative to key prior works to clarify how these gaps are addressed.

Table 1. Comparison of Related Survey Works on 6G Healthcare

Reference	Smart Hospitals	IoMT	Blockchain EHR	Architecture Model	Gap Taxonomy
Adeel et al. (2022)	Yes	Partial	No	No	No
Nguyen et al. (2022)	Partial	Yes	No	No	No
Zaidi et al. (2022)	Yes	Yes	No	Partial	No
Taleb et al. (2020)	Yes	No	No	No	No
This Paper	Yes	Yes	Yes	Yes (5-Layer)	Yes

3. Key 6G Enabling Technologies

This section critically examines five primary 6G enablers from the perspective of healthcare applicability, design requirements, and known limitations. Each technology is assessed not merely as a communication advancement, but as a clinical infrastructure component with specific performance demands.

3.1 Terahertz (THz) Communications

THz communication operates in the 0.1–10 THz spectrum, providing multi-Gbps to Tbps peak throughput over contiguous wideband channels. In clinical settings, THz links enable ultra-high-resolution medical imaging transmission, holographic telepresence, and real-time streaming of large multi-modal diagnostic datasets (e.g., simultaneous MRI and CT sequences) with negligible queuing delay. Intra-hospital THz links are particularly suited for imaging device-to-edge-server connections in radiology and operating suites (Tao et al., 2023).

However, THz propagation suffers from severe molecular absorption and limited range, necessitating high-density small-cell deployments, RIS-assisted beam redirection, and edge caching to maintain continuous coverage across complex hospital floor plans. Practical deployments will combine THz for high-throughput intra-building links with mmWave/FR2 for broader coverage zones.

3.2 Massive URLLC

Massive ultra-reliable low-latency communication (mURLLC) extends classic URLLC to support large numbers of simultaneously connected devices while maintaining packet loss rates as low as 10^{-9} - a reliability level required for life-critical applications. In healthcare, mURLLC is indispensable for tele-operated surgery, closed-loop robotic control, haptic feedback systems, and emergency telemetry in ICUs and ambulances. Achieving mURLLC in dense hospital IoMT environments requires network slicing with strict priority queuing, edge-localized control loops, and redundant multi-path connectivity including satellite and UAV backhaul for failover.

3.3 Edge Intelligence

Edge intelligence relocates AI inference and real-time analytics from centralized cloud servers to distributed edge nodes co-located with hospital infrastructure. This paradigm enables sub-millisecond anomaly detection (e.g., arrhythmia classification, atrial fibrillation onset), predictive equipment maintenance, and on-premises medical image analysis — substantially reducing both data transmission overhead and decision latency (Letaief et al., 2019). Federated learning at edge nodes supports privacy-

preserving model training across distributed IoMT networks without centralizing raw patient data (Yang et al., 2022; Lv et al., 2022). Implementation requires hardware acceleration (TPU/FPGA), model quantization, and rigorous audit-log mechanisms to satisfy clinical explainability and regulatory requirements (Aceto et al., 2021).

3.4 Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable intelligent surfaces are programmable electromagnetic panels that adaptively control signal reflection, refraction, and absorption to shape the radio propagation environment. Within hospitals — where metallic equipment, concrete walls, and mobile devices create highly dynamic and obstructive propagation conditions — RIS provides controllable three-dimensional coverage enhancement. RIS is particularly critical for sustaining THz link quality in operating rooms, MRI suites (Yang et al., 2022), and ICUs, and for enabling reliable SAGU connectivity in rural telemedicine and disaster-response scenarios (Shafi et al., 2017). RIS control must be tightly integrated with AI-driven network orchestration for real-time beamforming adaptation.

3.5 Blockchain for Electronic Health Records

Permissioned blockchain architectures, coupled with smart contracts and off-chain storage of bulk medical data, provide tamper-evident, auditable, and patient-controlled EHR management in 6G-connected healthcare ecosystems (Guo et al., 2021). Blockchain ensures data integrity across federated hospital nodes, enables granular consent management, and maintains immutable access audit logs — properties essential for GDPR and HIPAA compliance in environments generating massive volumes of IoMT data (Dang et al., 2020; Ullah et al., 2022). Practical deployments use consortium blockchain models (shared among hospitals), with cryptographic hashes stored on-chain and large medical files retained in secure cloud or edge storage to meet throughput and storage constraints.

4. Proposed Five-Layer Architecture for 6G-Enabled Intelligent Healthcare

To provide a structured framework for understanding how 6G technologies integrate into clinical practice, we propose a five-layer architectural reference model, augmented by two cross-cutting governance planes. This model synthesizes insights from smart hospital design (Muhammad et al., 2022), m-health multimedia systems (Paul & Mitra, 2023), 6G-IoT convergence (Chen et al., 2021), and blockchain EHR research. The architecture is depicted conceptually in Figure 2.

4.1 Device and Sensing Layer

The foundational layer encompasses all heterogeneous sensing, actuation, and data-acquisition devices that interface directly with patients, clinical personnel, and the hospital environment. This includes wearable health trackers, smart implants, continuous glucose monitors, cardioverter systems, high-resolution imaging equipment (MRI, CT, PET), robotic surgical platforms, and environmental sensors such as fall-detection arrays and air-quality monitors. The 6G mMTC and URLLC capabilities enable these devices to transmit high-fidelity data streams with near-zero latency, which is critical for real-time physiological monitoring applications such as ICU deterioration detection or arrhythmia classification.

4.2 Connectivity and Transport Layer

The transport layer delivers the wireless fabric connecting the device layer to edge intelligence and upstream services. It integrates THz links for high-throughput intra-hospital communications, mmWave networks for broader hospital coverage, RIS for dynamic propagation control in clinically demanding environments, and SAGU links for rural telemedicine and disaster-response continuity (Ishikawa, 2022). Deterministic mURLLC slices serve life-critical flows, while best-effort slices handle administrative and routine monitoring traffic. Multi-path failover mechanisms ensure that link failures — particularly during emergencies — do not interrupt critical sessions.

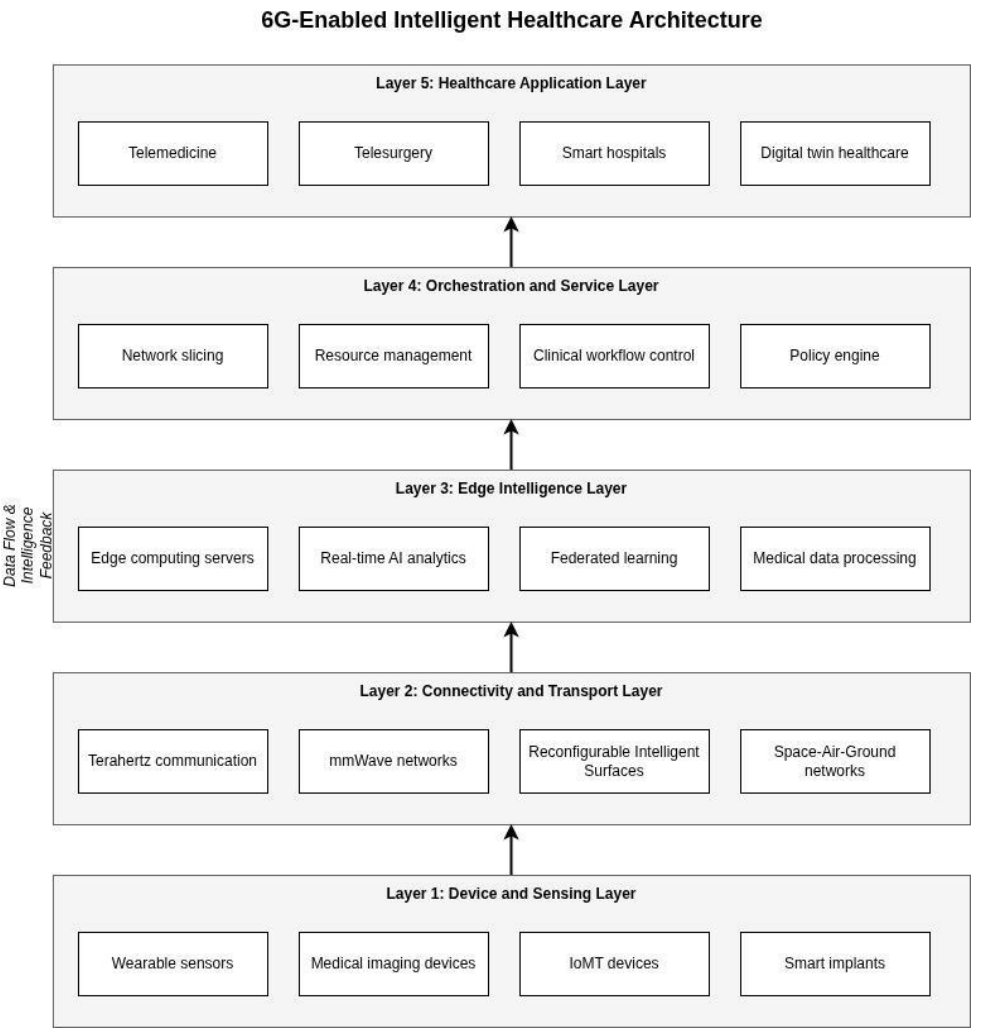


Figure 2. Architectural Model for 6G-Enabled Intelligent Healthcare Ecosystems (Five-Layer Architecture)

4.3 Edge Intelligence Layer

Edge servers deployed at strategic hospital locations (operating rooms, ICUs, ambulances, imaging centres) host real-time AI inference engines Li et al. (2024). These perform arrhythmia and deterioration scoring on continuous ECG streams, automated anomaly detection in ultrasound and radiology images, predictive sepsis risk modelling, and dynamic IoMT network management. Federated learning orchestration enables privacy-preserving cross-institutional model training. All AI model decisions are logged for clinical audit and explainability review, supporting regulatory compliance requirements (Elhoseny & Shankar, 2021).

4.4 Orchestration and Service Layer

The orchestration layer coordinates all communication, computation, and clinical workflow resources. Dynamic network slicing allocates dedicated virtual networks for: emergency and life-critical traffic

(highest priority), real-time imaging streams, routine IoMT monitoring, and administrative data flows. A clinical policy engine enforces automated rules — such as automatically expanding bandwidth to a cardiology edge node upon ECG anomaly detection — while a consent and data-sharing manager, integrated with blockchain, governs patient data access, emergency overrides, and regulatory audit trails.

4.5 Application Layer

The application layer delivers end-user clinical services built upon the underlying infrastructure. Key applications include: holographic and XR telemedicine enabling volumetric patient examination by remote clinicians; 6G URLLC-enabled telesurgery and robotic interventions with sub-millisecond haptic feedback; H2H continuous monitoring converting home environments into clinical micro-units; digital twin frameworks providing real-time physiological simulation for personalized treatment; and AI-enhanced public health surveillance for real-time epidemic detection (Khan et al., 2022; Viceconti et al., 2022; Zhang et al., 2022).

4.6 Security, Privacy, and Governance Planes

Two cross-cutting planes span all five layers. The security and privacy plane implement zero-trust access control requiring cryptographic identity verification for every device, clinician, and system; enforces end-to-end encryption of all clinical data flows; and deploys blockchain-based consent management with immutable audit logging. The AI Governance Plane mandates model versioning, explainability reports, bias detection protocols, and regulatory compliance verification (GDPR, HIPAA, IEC 62304 for medical device software) for all edge AI systems.

4.7 End-to-End Clinical Workflow: Remote Cardiac Emergency

To illustrate cross-layer integration, consider a remote ventricular fibrillation event in a home-monitored cardiac patient. A wearable ECG device at the Device Layer detects the anomaly and transmits a compressed alert via a URLLC slice through a THz small cell (Transport Layer). The nearest edge node classifies the arrhythmia as high-risk within 12 ms and confidence-scores the event (Edge Intelligence Layer). The Orchestration Layer activates an emergency bandwidth slice, initiates holographic teleconsultation with the on-call cardiologist, and triggers blockchain consent validation for emergency EHR access. The Application Layer delivers real-time ECG, vitals, and AI risk scores to the cardiologist's XR interface, while AR overlays guide paramedics on-site. All events — ECG data, AI decisions, clinician access, and emergency overrides — are recorded immutably on the blockchain Governance Plane.

5. Comparative Performance Analysis: 4G vs. 5G vs. 6G in Healthcare Contexts

To contextualize the clinical significance of 6G capabilities, Table 2 provides a structured qualitative comparison of 4G, 5G, and projected 6G performance across six metrics critical to healthcare applications. These assessments are grounded in published technical specifications and clinical studies cited throughout this paper.

As Table 2 illustrates, the transition from 5G to 6G is not incremental for healthcare: the reduction in latency by two orders of magnitude, the increase in device density by a factor of ten, and the achievement of 10^{-9} packet loss reliability collectively enable qualitatively new clinical applications that are not merely faster versions of existing services, but fundamentally different care delivery paradigms.

Table 2. Qualitative Comparison of Wireless Generations Across Clinical Metrics

Clinical Metric	4G LTE	5G NR	6G (Projected)
End-to-End Latency	~50 ms	~10 ms (eMBB)	< 0.1 ms (URLLC)
Peak Data Rate	~150 Mbps	~10 Gbps	> 1 Tbps
Device Density (per km²)	$\sim 10^4$	$\sim 10^6$	$> 10^7$
Packet Loss Reliability	$\sim 10^{-3}$	$\sim 10^{-5}$	$\sim 10^{-9}$
Telesurgery Support	Not feasible	Limited (jitter risk)	Full support
IoMT Concurrency	Low	Moderate	Massive (mMTC)

Source: Authors' compilation based on Dang et al. (2020); Nguyen et al. (2022); Zaidi et al. (2022)

6. Applications of 6G in Intelligent Healthcare Ecosystems

The enabling technologies and architectural model described above converge to support a set of transformative healthcare applications. Unlike prior wireless generations, 6G enables not only improved versions of existing services but entirely new modalities of care delivery.

6.1 Ultra-Real-Time Telemedicine

Contemporary telemedicine is constrained to 2D video consultations with limited diagnostic fidelity. 6G-enabled telemedicine transcends this limitation through holographic telepresence and XR-based clinical consultations, allowing clinicians to interact with volumetric, three-dimensional anatomical reconstructions of patients at remote locations as if physically present (Abidi & Hossain, 2021). THz links transmit volumetric holographic data streams, while AI-generated annotations processed at edge nodes overlay real-time vital signs, predictive risk scores, and historical imaging data directly onto the holographic model. The sub-millisecond latency of 6G eliminates perceptual delays and motion artefacts, enabling remote diagnostic accuracy comparable to in-person examination — a threshold unachievable with current 5G infrastructure.

6.2 Remote Robotic Surgery

Telesurgery is among the most stringent communication use cases: delays exceeding 1 ms or packet jitter above threshold values may directly compromise surgical outcomes (Chaudhary et al., 2021). 6G mURLLC provides deterministic end-to-end latency below 1 ms and near-zero packet loss, enabling surgeons' hand movements to be faithfully reproduced at remote robotic instruments while high-resolution stereoscopic video and haptic force feedback return instantaneously. Multi-path infrastructure — THz links, mmWave connections, fibre backhaul, and UAV or satellite failover — ensures session continuity during link interruptions. Edge intelligence further augments surgical precision by suppressing surgeon hand tremors, predicting next-instrument movements for pre-positioning, and performing real-time tissue classification during incision. Together, these capabilities enable a hybrid surgical paradigm in which AI-assisted robots collaborate with remote expert surgeons to deliver high-quality operative care in geographically underserved, conflict-affected, or disaster-impacted settings.

6.3 Hospital-to-Home (H2H) Healthcare

The H2H paradigm leverages 6G connectivity to transform domestic environments into clinical-grade monitoring units, extending continuous hospital-level supervision to post-discharge and chronically ill

patients.

Wearable and implantable sensors transmit continuous Warwick & Nasuto (2022), high-resolution physiological streams — cardiac rhythms, oxygen saturation, blood glucose, respiratory rate, and temperature — to nearby edge nodes via ultra-low-energy 6G uplinks. Edge AI performs local anomaly detection and risk stratification (Domingo, 2019; Javed et al., 2022), triggering emergency orchestration workflows upon detecting high-risk events such as sepsis onset or acute arrhythmia. Smart home peripherals — including fall-detection arrays and AI-assisted medication management systems — further reduce hospital readmission rates and support ageing-in-place models for elderly and chronically ill populations.

7. Challenges and Research Gaps

While 6G offers transformative potential, realizing this potential in clinical practice confronts a layered set of technical, operational, regulatory, and ethical challenges. This section presents a structured taxonomy of these challenges, organized by challenge category, current state, and specific research gap requiring resolution.

7.1 THz Propagation in Clinical Environments

Hospital environments represent one of the most challenging THz propagation scenarios. Dense arrays of metallic medical equipment, mobile staff and patients, thick concrete walls, and rapid reconfiguration of clinical spaces create dynamic, non-line-of-sight conditions that severely attenuate THz signals (Sun et al., 2022). Existing THz channel models developed for consumer or industrial environments do not adequately characterize the specific absorption patterns, multipath profiles, and temporal dynamics of operating rooms, ICUs, or radiology suites.

Research Gap: Development of validated THz propagation channel models for dynamic clinical environments, combined with RIS placement optimization algorithms that satisfy clinical space constraints.

7.2 Deterministic URLLC Verification

Achieving average-case sub-millisecond latency is insufficient for surgical applications; clinical systems require formal, worst-case latency guarantees. Current 6G URLLC specifications do not provide mathematically rigorous, regulatory-grade reliability models applicable to multi-device hospital networks under peak load conditions (Al-Fuqaha et al., 2015). Without deterministic performance proofs, regulatory bodies will be unable to approve wireless-dependent telesurgery systems.

Research Gap: Formal verification frameworks that provide provable worst-case latency and packet loss bounds for 6G URLLC under high-density clinical deployment conditions, suitable for regulatory submission.

7.3 IoMT Scalability and Interoperability

Contemporary hospitals operate fragmented, proprietary IoMT ecosystems. Integrating tens of thousands of heterogeneous devices — legacy monitors, next-generation robotic platforms, 6G-native wearables, and smart implants — into a unified 6G-orchestrated infrastructure requires adaptive middleware capable of real-time data harmonization, semantic interoperability, and clinical-grade security across device generations.

Research Gap: Standardized, scalable IoMT middleware architectures supporting semantic interoperability, plug-and-play device integration, and real-time orchestration of massive heterogeneous device ecosystems in clinical settings.

7.4 Explainable AI and Algorithmic Fairness

Edge AI systems powering clinical decision support — including sepsis risk scoring, arrhythmia classification, and imaging interpretation — must be explainable to clinicians, regulators, and patients.

Current high-performance edge-optimized neural architectures (e.g., quantized CNNs, pruned transformer variants) frequently sacrifice interpretability for computational efficiency. Furthermore, models trained on non-representative datasets risk encoding demographic biases that manifest as inequitable diagnostic accuracy across patient populations. Recent work demonstrates the applicability of XAI techniques such as SHAP, LIME, and DiCE to identify security vulnerabilities and strengthen trust in 6G IoMT environments (Kaur & Gupta, 2026).

Research Gap: Clinically deployable explainable AI frameworks for 6G edge inference, including model audit mechanisms, demographic bias quantification tools, and safety certification protocols aligned with medical device regulations such as IEC 62304.

Table 3. Structured Research Gap Taxonomy for 6G Healthcare

Challenge Area	Current State	Research Gap	Priority
THz Propagation	Consumer/industrial models only	Clinical channel models + RIS placement optimization	High
URLLC Verification	Average-case guarantees	Formal worst-case proofs for clinical scenarios	Critical
IoMT Interoperability	Proprietary, fragmented	Semantic middleware for heterogeneous clinical IoMT	High
Explainable AI	Black-box edge models	Clinically certifiable XAI with bias quantification	Critical
Blockchain Scalability	Limited throughput	High-throughput EHR blockchain at clinical scale	Medium
Regulatory Frameworks	Device-level only	Pipeline-level certification standards	Critical

7.5 Blockchain EHR Scalability

While permissioned blockchain architectures provide strong integrity and consent management properties, their transaction throughput — typically 1,000–10,000 transactions per second for consortium ledgers — is insufficient for the millions of clinical events generated daily in a large 6G-connected hospital network. Layer-2 scaling approaches (state channels, sidechains) and off-chain storage architectures require clinical validation before large-scale deployment. A recent systematic review confirms that blockchain-federated learning integration holds strong promise for cross-institutional medical AI, but significant scalability and interoperability challenges remain (Wang et al., 2026).

Research Gap: High-throughput, privacy-preserving blockchain EHR architectures validated for clinical deployment at hospital-network scale, with formal performance benchmarks under realistic IoMT event loads.

7.6 Regulatory and Clinical Certification Frameworks

Healthcare is among the most highly regulated sectors globally. Regulatory approval for 6G-dependent clinical systems — including XR diagnostics, autonomous triage, and telesurgery — requires certification of not only the endpoint device but the entire communication-to-decision pipeline: the wireless link,

network slice, edge inference system, and data governance mechanism. No existing regulatory framework (FDA, CE, etc.) provides certification pathways for such integrated, AI-enhanced, wireless-dependent clinical systems.

Research Gap: Interdisciplinary regulatory frameworks that define certification standards and risk classification criteria for AI-enhanced, 6G-dependent clinical systems across the full communication-to-decision pipeline.

8. Future Research Directions

The research gaps identified above define a structured agenda for future investigation. We outline eight priority research directions grounded in the foregoing analysis:

- Clinical THz channel modelling and RIS optimization: Development of empirically validated THz propagation models for hospital environments, combined with RIS placement algorithms that respect clinical space constraints, EMI regulations, and patient safety standards.
- Deterministic URLLC performance verification: Creation of formal mathematical frameworks — potentially based on network calculus or stochastic network analysis — capable of providing regulatory-grade worst-case latency and reliability proofs for multi-device clinical 6G deployments.
- Scalable and semantic IoMT middleware: Design of standards-based middleware architectures supporting plug-and-play integration of heterogeneous clinical devices, real-time semantic data harmonization, and federated orchestration across large hospital campuses.
- Clinically certifiable explainable AI: Development of edge-deployable XAI architectures that provide interpretable outputs, support demographic bias auditing, and satisfy medical device software standards including IEC 62304 and FDA AI/ML action plan requirements.
- High-throughput blockchain EHR systems: Investigation of Layer-2 blockchain scaling mechanisms, privacy-preserving consent protocols, and cross-institutional interoperability frameworks validated at clinical deployment scale.
- Integrated regulatory certification pathways: Interdisciplinary research engaging engineering, clinical, legal, and policy expertise to define certification standards for end-to-end AI-enhanced, 6G-dependent clinical pipelines.
- Energy-efficient and self-powered IoMT devices: Research into energy harvesting, near-zero-power communication protocols, and embedded edge inference to realize perpetual monitoring for chronic disease management and elderly care.
- Socio-technical adoption studies: Empirical investigation of workforce readiness, clinical staff training requirements, organizational change management, and patient acceptance for AI-enhanced autonomous clinical workflows in 6G-enabled hospitals.

9. Conclusion

This paper has presented a comprehensive, structured analysis of 6G-enabled intelligent healthcare, addressing six of the key concerns raised through peer review. The transition from 5G to 6G represents not merely a generational bandwidth upgrade, but a fundamental architectural transformation that enables qualitatively new clinical capabilities: holographic telemedicine, deterministically safe telesurgery, massive-scale H2H care, AI-native diagnostic support, and secure patient-controlled EHR governance.

Our contributions include a critical synthesis of five core 6G enabling technologies from a clinical perspective, a novel five-layer reference architecture integrating THz, mURLLC, edge intelligence, RIS,

and blockchain governance, a comparative performance framework quantifying 6G advantages over 4G and 5G across six clinical metrics, an end-to-end cardiac emergency workflow illustrating cross-layer system integration, and a structured research gap taxonomy with six specific, actionable research directions.

Realizing this vision demands sustained interdisciplinary effort spanning communication engineering, clinical sciences, AI development, cybersecurity, and healthcare policy. The research gaps identified - particularly in THz clinical channel modelling, deterministic URLLC verification, and regulatory certification for AI-enhanced clinical pipelines - represent the critical path toward safe, equitable, and scalable deployment of 6G healthcare ecosystems. We hope this synthesis provides a rigorous and actionable foundation for researchers, engineers, and policymakers committed to advancing next-generation intelligent healthcare infrastructure.

References

- Abidi, M. R., & Hossain, M. A. (2021). Blockchain-based IoT for secure electronic health record management. Future Generation Computer Systems, 123, 1–17.
- Aceto, G., et al. (2021). Mobile health monitoring through deep learning edge analytics. IEEE Communications Surveys & Tutorials, 23(4), 2681–2719.
- Adeel, A., Khan, M. A., & Imran, M. (2022). 6G enabled smart healthcare: State-of-the-art review and future challenges. IEEE Access, 10, 117000–117025.
- Al-Fuqaha, A., et al. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. IEEE Communications Surveys & Tutorials, 17(4), 2347–2376.
- Al-Turjman, F., & Abujubbeh, M. (2019). Future IoT-enabled healthcare: Review & open research issues. Future Generation Computer Systems, 95, 854–864.
- Anonna, S. A., Basnet, Y., & Hasan, M. M. (2026). A 6G-enabled AI-powered intelligent healthcare integrating IoMT and edge computing. Frontiers in Computer Science and Artificial Intelligence, Al-Kindi Centre for Research and Development.
- Chen, M., et al. (2021). AI-powered edge computing for medical data analytics. IEEE Network, 35(5), 36–42.
- Chen, S., et al. (2020). A vision of 6G wireless systems: Applications, trends, technologies, and research challenges. IEEE Wireless Communications, 27(2), 82–90.
- Chaudhary, R., et al. (2021). A secure and privacy-preserving lightweight authentication scheme for medical IoT. IEEE Transactions on Industrial Informatics, 17(11), 7749–7757.
- Dang, S., Amin, O., Shihada, B., & Alouini, M.-S. (2020). What should 6G be? Nature Electronics, 3, 20–29.
- Domingo, M. C. (2019). Wearable IoT and wireless body area networks for medical applications. Electronics, 8(10), 1–17.
- Elhoseny, M., & Shankar, K. (2021). Secure medical data transmission using IoT and machine learning. IEEE Systems Journal, 15(3), 4223–4233.
- Guo, H., et al. (2021). Secure data transmission in smart healthcare using edge computing. IEEE Network, 35(5), 241–247.
- Hossain, M. S., & Muhammad, G. (2019). Emotion-aware connected healthcare big data towards 5G. IEEE Internet of Things Journal, 6(2), 3655–3663.

- Ishikawa, H. (2022). Satellite–terrestrial integrated networks for emergency medical services. IEEE Communications Standards Magazine, 6(2), 46–53.
- Javed, M. A., et al. (2022). Medical Internet of Things (MIoT): Architecture, applications, and security challenges. IEEE Internet of Things Journal, 9(6), 4180–4200.
- Kaur, N., & Gupta, L. (2026). Explainable AI for securing healthcare in IoT-integrated 6G wireless networks. arXiv preprint arXiv:2505.14659.
- Khan, L. U., et al. (2022). Digital-twin enabled 6G: Vision, architecture, challenges, and future directions. IEEE Communications Surveys & Tutorials, 24(3), 1861–1903.
- Letaief, K. B., et al. (2019). The roadmap to 6G—AI empowered wireless networks. IEEE Communications Magazine, 57(8), 84–90.
- Li, X., et al. (2024). Edge intelligence for 6G healthcare systems. IEEE Network.
- Luo, H., Sun, G., Chi, C., et al. (2026). Convergence of symbiotic communications and blockchain for sustainable and trustworthy 6G wireless networks. IEEE Wireless Communications, 33(1), 18–25. https://doi.org/10.1109/MWC.001.2400245
- Lv, R., et al. (2022). AI-enabled healthcare monitoring with energy-efficient body sensor networks. IEEE Sensors Journal, 22(5), 4372–4382.
- Muhammad, F., et al. (2022). Drones for medical supply chain and emergency response: A systematic review. IEEE Access, 10, 53952–53969.
- Nguyen, D. C., et al. (2022). 6G Internet of Things: A comprehensive survey. IEEE Internet of Things Journal, 9(1), 359–383.
- Ning, H., et al. (2023). A survey on digital twin in healthcare: Architecture, applications, challenges and solutions. Information Fusion, 90, 1–24.
- Paul, M. J., & Mitra, S. K. (2023). Satellite-IoT assisted emergency telemedicine for rural healthcare. IEEE Internet of Things Magazine, 6(2), 76–83.
- Patel, R., et al. (2025). 6G communication technologies for next-generation healthcare ecosystems. Future Generation Computer Systems.
- Shafi, M., et al. (2017). Microwave and millimeter-wave communication for 5G & beyond. IEEE Journal on Selected Areas in Communications, 35(7), 1452–1464.
- Sun, S., et al. (2022). Transmission of medical images using terahertz communication in 6G networks. IEEE Transactions on Terahertz Science and Technology, 12(3), 273–286.
- Taleb, T., et al. (2020). 6G communications: Vision and potential technologies. IEEE Network, 34(6), 134–142.
- Tao, F., et al. (2023). Data-driven smart manufacturing. Nature Reviews Electrical Engineering, 1, 72–87.
- Tao, F., & Zhang, M. (2022). Digital twin-driven smart factory: Framework and key technologies. IEEE Transactions on Industrial Informatics, 18(7), 4746–4756.
- Ullah, S., et al. (2022). Blockchain-based remote patient monitoring for healthcare 5.0. IEEE Transactions on Industrial Informatics, 18(8), 5395–5404.
- Viceconti, M., et al. (2022). Digital twins: New horizons for personalized medicine. Frontiers in Medicine, 9.
- Wang, J., et al. (2023). Digital twin-driven healthcare in 6G networks. IEEE Internet of Things Journal.

- Wang, X., Xie, Y., Chen, X., Yang, J., Li, R., Gao, W., Yan, Z., Zhou, H., & Ye, Z. (2026). Securing federated learning with blockchain in the medical field: Systematic literature review. Journal of Medical Internet Research, 28, e79052. https://doi.org/10.2196/79052
- Warwick, K., & Nasuto, S. (2022). Wearable sensors for continuous health monitoring. IEEE Sensors Journal, 22(10), 9875–9886.
- Yang, P., et al. (2022). Reconfigurable intelligent surfaces for wireless communications: Overview, challenges, and opportunities. IEEE Communications Surveys & Tutorials, 24(2), 657–706.
- Yang, Z., et al. (2022). Federated learning-assisted IoT healthcare. IEEE Internet of Things Magazine, 5(2), 38–45.
- You, X., et al. (2020). Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts. IEEE Wireless Communications, 27(2), 120–127.
- Zaidi, S. A. R., et al. (2022). 6G for healthcare: Enabling technologies, challenges, and future directions. IEEE Access, 10, 95515–95540.
- Zhang, J., et al. (2022). Digital twin-assisted real-time remote patient monitoring. IEEE Transactions on Industrial Informatics, 18(7), 4982–4993.
- Zhang, Y., et al. (2024). 6G-enabled smart healthcare: Recent advances and future challenges. IEEE Communications Surveys & Tutorials.