

Review Article

Computer Science

Internet of Things (IoT) in Modern Healthcare: A Structured Narrative Review of Technologies, Clinical Evidence, Challenges, and Future Perspectives

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Abstract

Background: The Internet of Medical Things (IoMT) connects sensors, wearable and implantable devices, gateways, networks, computing platforms, electronic health records, and decision-support services. Its value depends on valid measurement, dependable communication, workflow integration, cybersecurity, interoperability, and accountable analytics.

Objective: To provide a transparent structured narrative synthesis of contemporary IoMT technologies, clinical deployments, and comparative architecture trade-offs healthcare-specific security and interoperability requirements, and the maturity of federated learning, digital twins, explainable Artificial Intelligence (AI), and secure AI.

Methods: PubMed/MEDLINE and targeted searches of IEEE Xplore, Scopus, Web of Science, ACM Digital Library, and Google Scholar were used to identify English-language evidence published primarily from January 2021 to September 20, 2026; seminal standards and foundational studies were retained when needed. Searches combined IoT/IoMT terms with healthcare, wearables, remote monitoring, edge/fog/cloud, 5G, THz, cybersecurity, interoperability, federated learning, digital twins, and explainable AI. This is a structured narrative review, not a PRISMA systematic review; evidence was prioritized by clinical relevance, recency, methodological strength, and deployment maturity (Baethge, Goldbeck-Wood, & Mertens, 2019; Page et al., 2021).

Results: Thirty core sources were retained, including primary clinical and implementation studies, systematic/scoping reviews, technical reviews, standards, regulatory guidance, and a 2026 analytical study of mobility-aware THz reliability. Bluetooth Low Energy is suited to low-power wearable links; Wi-Fi to high-throughput managed environments; 5G to mobile wide-area services; and wireless body area networks to coordinated on-body sensing. Edge computing reduces response time and data exposure, whereas cloud computing improves elasticity while increasing connectivity and concentration risks. Secure lifecycle management and clinically relevant testing are more appropriate than generic antivirus rankings. Federated learning and explainable AI are translational, while patient digital twins remain predominantly preclinical (S. R. Abbas, Z. Abbas, Zahir, & Lee, 2024; Ahmadi et al., 2019; Allen, 2024; Drummond & Gonsard, 2024; Freyer, Groß, & Lipprandt, 2024; Health Level Seven International, 2023; Hernandez-Jaimes, Martínez-Cruz, Ramírez-Gutiérrez, & Feregrino-Urbe, 2023; IEEE Standards Association, n.d.; Lu et al., 2024; Messinis et al., 2024; National Institute of Standards and Technology, 2021; Nguyen et al., 2026; Panahi, 2026; Patel et al., 2023; Rani, Kataria, Kumar, & Tiwari, 2023; Rosenbacke, Melhus, McKee, & Stuckler, 2024; Shen, Chen, & Ding, 2024; Sun et al., 2018; Teo et al., 2024; Torab-Miandoab, Samad-Soltani, Jodati, & Rezaei-Hachesu, 2023; U.S. Food and Drug Administration, 2026; van Kolschooten & van Oirschot, 2024; Wettstein et al., 2024; Zakerabasali & Ayyoubzadeh, 2022).

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Conclusions: IoMT is moving from isolated pilots toward integrated clinical infrastructure, but readiness remains uneven. Near-term deployment should prioritize validated sensing, resilient hybrid edge-cloud architectures, standards-based exchange, lifecycle cybersecurity, explicit clinical escalation, and prospective outcome evaluation. Beyond-5G/THz links may support future high-data-rate services, but mobility-related beam misalignment and tracking delay must be included in reliability and outage analysis (Panahi, 2026).

Keywords: Internet of Things; Internet of Medical Things; IoMT; remote patient monitoring; edge AI; cybersecurity; interoperability; federated learning; digital twins; explainable AI; terahertz communication.

Introduction

Healthcare is shifting from episodic encounters toward longitudinal, distributed, and data-informed care. IoMT provides the technical substrate by connecting physiological and environmental sensors, wearable or implantable devices, local gateways, communication networks, computing platforms, and clinical information systems. This ecosystem supports Remote Patient Monitoring (RPM), chronic-disease management, assisted living, emergency coordination, and smart-hospital operations (T. Abbas et al., 2024; El-deep, Abohany, Sallam, & Abd El-Mageed, 2025; Huang, Wang, Wang, & Zhang, 2023; Shah et al., 2026).

An IoMT service is clinically useful only when measurements are valid, transmission is sufficiently timely and reliable, alerts are actionable, information is semantically interoperable, and security failures do not create unacceptable patient-safety risks. Recent evidence also shows a persistent translation gap between technically promising prototypes and systems evaluated in routine workflows (T. Abbas et al., 2024; El-deep et al., 2025; Huang et al., 2023; Nguyen et al., 2026; Shah et al., 2026).

This review asks: Which sensing, connectivity, computing, and AI technologies enable modern IoMT? What does recent clinical evidence show? What trade-offs determine architecture selection? How mature are federated learning, digital twins, explainable AI, secure AI, and emerging high-frequency mobile links?

Review Methodology

Design and reporting

The article is explicitly framed as a structured narrative review. PRISMA 2020 requires complete reporting of information sources, full search strategies, selection procedures, study flow, and risk-of-bias methods (Page et al., 2021). Because the original work did not prospectively implement duplicate screening or design-specific risk-of-bias assessment, retrospective presentation as a fully PRISMA-compliant systematic review would overstate rigor. SANRA was used as a writing and self-audit framework (Baethge et al., 2019).

Search and eligibility

The evidence update covered January 1, 2021 to September 20, 2026. PubMed/MEDLINE was searched directly; targeted searches also covered IEEE Xplore, Scopus, Web of Science, ACM Digital Library, Google Scholar, publisher platforms, and FDA, NIST, HL7, and IEEE resources. The core concept was: («Internet of Things» OR IoT OR «Internet of Medical Things» OR IoMT) AND (healthcare OR medical OR telemedicine OR «patient monitoring») AND (sensor* OR wearable* OR Bluetooth OR Wi-Fi OR 5G OR terahertz OR THz OR edge OR fog OR cloud OR cybersecurity OR interoperability OR FHIR OR «federated learning» OR «digital twin*» OR «explainable AI»).

Eligible sources addressed human healthcare or clinical operations and reported an IoMT architecture, enabling technology, clinical or implementation outcome, healthcare-specific security or privacy control, interoperability requirement, or maturity

evidence for emerging analytics and communications. Reviews supplied broad synthesis; primary studies were prioritized for clinical claims. Non-health IoT studies, commercial webpages, duplicates, sources without adequate methodological detail, and claims lacking a stable publication were excluded.

Selection and appraisal

Screening and extraction for this narrative update were performed by the author at title/abstract and full-text levels, with backward citation checking of high-value reviews. Data were charted by publication type, application, device/sensor, connectivity, computing location, outcome, limitation, and maturity. Evidence was weighted qualitatively: randomized/prospective studies, large implementations, explicit systematic/scoping reviews, standards, and regulatory guidance received greater interpretive weight. No meta-analysis was undertaken because interventions and outcomes were heterogeneous.

Results

Evidence profile

The final synthesis used 30 core sources: four recent clinical or health-system implementation studies (Lu et al., 2024; Nguyen et al., 2026; Patel et al., 2023; Wettstein et al., 2024); systematic, scoping, or comprehensive reviews addressing IoMT, security, interoperability, federated learning, digital twins, XAI, ethics, and healthcare technology (S. R. Abbas et al., 2024; T. Abbas et al., 2024; Ahmadi et al., 2019; Allen, 2024; Drummond & Gonsard, 2024; El-deep et al., 2025; Freyer et al., 2024; Hernandez-Jaimes et al., 2023; Huang et al., 2023; Messinis et al., 2024; Rani et al., 2023; Rosenbacke et al., 2024; Shah et al., 2026; Shen et al., 2024; Sun et al., 2018; Teo et al., 2024; Torab-Miandoab et al., 2023; Zakerabasali & Ayyoubzadeh, 2022); regulatory and standards sources (Health Level Seven International, 2023; IEEE Standards Association, n.d.; National Institute of Standards and Technology, 2021; U.S. Food and Drug Administration, 2026); review-methodology sources (Baethge et al., 2019; Page et al., 2021); and one 2026 IEEE Communications Letters analytical study used specifically to qualify future mobile THz reliability claims (Panahi, 2026). This substantially expands the original six-reference base. (Table 1)

Clinical applications

RPM has the strongest contemporary clinical evidence among IoMT applications. A large wearable telemedicine RCT reported lower hospitalization and major adverse cardiac-event hazards over 12 months (Lu et al., 2024). An interoperable smartwatch system demonstrated acceptable usability and sustained data availability (Wettstein et al., 2024), while post-discharge activity streams improved risk prediction without proving that alerts themselves improve outcomes (Patel et al., 2023).

Smart-hospital evidence increasingly concerns operational integration. A 2026 eight-hospital implementation connected a wearable to Epic and a continuously staffed virtual operations center; it demonstrated scalability and alert-governance feasibility,

Table 1: Representative evidence.

Study	Design / setting	Technology/domain	Main evidence	Limitations
Lu et al. (2024)	Open-label RCT; 1,248 older adults with CHD	Wearable multiparameter telemedicine	12-month hospitalization HR 0.59; MACE HR 0.60	Open-label; single context
Wettstein et al. (2024)	Randomized activeDCM evaluation; 95 completers	Smartwatch, app, interoperable server/viewer	Usability 78; sensor data on 78% of days	Adherence varied; device effect not isolated
Patel et al. (2023)	Randomized trial; 500 post-discharge patients	Phone/wearable activity; cloud ML	Activity improved 30-day risk prediction	Prediction does not prove improved outcomes
Nguyen et al. (2026)	Eight-hospital implementation; ~2,700 beds	FDA-cleared wearable; Wi-Fi; Epic; virtual center	>95% use; 100% nurse training; ~50% alerts filtered	Non-randomized; operational outcomes
Messinis et al. (2024)	Comprehensive review	AI-enabled IoMT cybersecurity	Maps attacks and defenses across architecture	Limited prospective clinical validation
Torab-Miandoab et al. (2023)	Systematic review; 36 studies	FHIR, CDA, SNOMED CT, APIs	Defines syntactic/semantic requirements	Broader HIS scope; variable maturity
Teo et al. (2024)	Systematic review	Federated healthcare ML	Maps clinical and technical architectures	Mostly retrospective/experimental
Drummond and Gonsard (2024)	Scoping review; 80 claimed twins	Patient digital twins	98% were preclinical	Inconsistent definitions and validation
Panahi (2026)	Closed-form analytical communication study	Mobile THz beam tracking	Models velocity-dependent misalignment and tracking-latency outage	Not a healthcare deployment study

but randomized evidence on mortality, escalation timing, cost-effectiveness, and equity remains necessary (Nguyen et al., 2026). (Table 2)

No technology is universally superior. BLE-to-phone-to-cloud conserves battery but inherits smartphone availability and pairing risks; Wi-Fi supports high volume but requires roaming and segmentation; and 5G provides mobility but does not guarantee end-to-end clinical latency. THz communication is a longer-horizon option whose reliability is unusually sensitive to blockage and pencil-beam alignment. Panahi (2026) shows through closed-

form outage analysis why terminal velocity and beam-tracking latency must be modeled jointly rather than treating alignment error as static. For safety-critical healthcare, redundancy, buffering, timestamp integrity, and a defined safe state remain more important than peak data rate. (Table 3)

Edge AI is appropriate when the response deadline is shorter than dependable cloud round-trip latency, raw signals are sensitive, or connectivity is intermittent. Cloud analytics remain preferable for intensive training and longitudinal inference. Clinically acceptable AI also requires calibration, external and

Table 2: Communication technologies

Technology	Latency / energy / capacity	Reliability and security constraints	Best-fit scenario
BLE	Very low power; short range; modest throughput	Pairing/key management, interference, gateway dependence	Wearables and home monitoring
Wi-Fi	High throughput; low-to-moderate local latency	Congestion, roaming, credentials, higher endpoint energy	Hospitals, home hubs, bedside gateways
5G/cellular	Wide-area mobility; high capacity; potentially low latency	Coverage, handover, operator dependence, subscription cost	Ambulances and community monitoring
WBAN	Coordinates multiple on-/in-body sensors	Body attenuation, coexistence, gateway failure	Multisensor patches and implants
LPWAN	Long range; low energy; low throughput	Payload/downlink limits and variable delay	Low-rate rural/home sensing
THz / beyond-5G	Extremely high prospective data rates; highly directional links	Blockage, molecular loss, narrow-beam misalignment, tracking latency and mobility-sensitive outage (Panahi, 2026)	Future imaging/data offload and short-range high-capacity links; not ready for routine clinical telemetry

Table 3: Computing and AI.

Platform	Strengths	Constraints	Best fit
Device/TinyML	Minimum response time and raw-data movement	Severe memory, battery, update, and explainability constraints	Bounded signal checks and urgent triggers
Edge gateway	Low latency; multisensor aggregation; local privacy policy	Gateway outage/compromise affects multiple devices	Home hub, bedside, ambulance
Fog/hospital edge	Near-site shared compute; institutional control	Orchestration, identity, and state complexity	Smart ward and local IDS
Cloud	Elastic compute/storage; training and longitudinal analytics	Network, concentration, vendor, and governance risk	Population analytics and EHR integration
Hybrid	Local urgent action plus scalable central analysis	Most complex to test and synchronize	Safety-relevant RPM and smart hospitals

prospective validation, subgroup analysis, uncertainty handling, drift monitoring, and a human escalation path (T. Abbas et al., 2024; El-deep et al., 2025; Hernandez-Jaimes et al., 2023; Huang et al., 2023; Messinis et al., 2024; Shah et al., 2026).

IoMT threat modeling must connect cyber events to clinical harm. Assets include sensor fidelity, patient identity, medication or device commands, alarms, availability, location, records, model parameters, and audit trails. Threats occur at device, communication, edge/cloud, and AI layers (Hernandez-Jaimes et al., 2023; Messinis et al., 2024; National Institute of Standards and Technology, 2021; U.S. Food and Drug Administration, 2026). (Table 4)

Current FDA guidance frames cybersecurity across the total product lifecycle and expects threat modeling, security architecture, testing, SBOMs, vulnerability management, and secure updates. NIST SP 800-213 supports risk-based device requirements before acquisition (National Institute of Standards and Technology, 2021; U.S. Food and Drug Administration, 2026). The indirect antivirus-ranking citation in the original manuscript has therefore been removed.

Interoperability spans technical connectivity, syntactic structure, semantic meaning, and workflow integration. HL7 FHIR supports modular clinical information exchange; IEEE 11073 addresses personal and point-of-care device exchange;

terminologies such as SNOMED CT and LOINC preserve meaning. Conformance testing must also verify device identity, patient association, units, timing, provenance, calibration, uncertainty, alarm status, downtime behavior, and end-to-end workflow (Health Level Seven International, 2023; IEEE Standards Association, n.d.; Torab-Miandoab et al., 2023). (Table 5)

Federated learning is not inherently private or secure: updates can leak information, malicious clients can poison aggregation, and non-IID clinical data can reduce fairness or convergence. Deployment requires governance, a threat model, authenticated participants, secure/robust aggregation, privacy accounting, external validation, and monitoring (S. R. Abbas et al., 2024; Rani et al., 2023; Teo et al., 2024).

A credible digital twin should be patient specific, dynamically updated, linked to a defined decision, and evaluated through verification, validation, and uncertainty quantification. A 2024 scoping review found 98% of 80 claimed patient twins in preclinical phases (Drummond & Gonsard, 2024). Explainability is likewise not a substitute for validation; explanations can support error detection but also create overtrust, and their effects on clinician trust are mixed (Allen, 2024; Freyer et al., 2024; Rosenbacke et al., 2024).

Table 4: Security, privacy, and interoperability

Lifecycle stage	Threat examples	Required controls
Onboarding	Counterfeit device, shared credential, exposed debug port	Unique identity; secure boot; signed inventory/SBOM; disabled debug
Operation	Spoofing, replay, interception, lateral movement	Mutual authentication; encryption; key rotation; segmentation; least privilege
Monitoring	Undetected compromise, alert flooding, ransomware	Security logging; anomaly monitoring; clinical-severity triage; tested recovery
Maintenance	Unsigned patches, vulnerable dependencies, end-of-support	Signed updates; rollback protection; disclosure; patch SLAs; penetration testing
Decommissioning	Residual data and active credentials	Cryptographic erasure; certificate revocation; account closure
AI lifecycle	Poisoning, leakage, adversarial input, drift	Provenance; robust aggregation; privacy controls; model signing; subgroup/drift monitoring

Table 5: Emerging technologies.

Technology	Proposition	Principal barriers	Readiness
Federated learning	Distributed model training without central raw-data pooling	Update leakage/poisoning, non-IID data, communication cost, governance	Translational (S. R. Abbas et al., 2024; Rani et al., 2023; Teo et al., 2024)
Digital twins	Patient-/organ-specific dynamic representation	Definition, data assimilation, uncertainty, compute, regulation	Predominantly preclinical (Drummond & Gonsard, 2024; Shen et al., 2024)
Explainable AI	Communicates factors behind an AI output	Unfaithful explanations, automation bias, user mismatch	Translational; mixed trust evidence (Allen, 2024; Freyer et al., 2024; Rosenbacke et al., 2024)
Secure AI	Robust/private AI across device-edge-cloud	Dataset shift, adaptive attacks, false alarms, overhead	Prototype to translational (S. R. Abbas et al., 2024; Hernandez-Jaimes et al., 2023; Messinis et al., 2024; Rani et al., 2023; Teo et al., 2024)
Mobile THz links	Directional ultra-high-capacity future connectivity	Velocity-dependent beam error, tracking delay, blockage, outage (Panahi, 2026)	Analytical/preclinical for healthcare

Discussion

Risk-based architecture

Architecture selection should begin with the clinical hazard and response deadline. Wellness tracking can tolerate delayed synchronization; deterioration alarms require bounded delay, reliable timing, local buffering, escalation ownership, and a documented safe state. Hybrid edge-cloud designs often retain urgent functions locally while using cloud resources for longitudinal analytics and fleet management.

Energy, latency, reliability, scalability, security, and usability are coupled. Higher sampling and radio use shorten battery life; cloud centralization increases bandwidth and concentration risk; privacy controls consume compute; and sensitive thresholds worsen alert fatigue. Future high-frequency networks do not remove this systems problem. In mobile THz links, narrow-beam reliability depends on motion and the speed of beam reacquisition; outage analysis should therefore include velocity-dependent misalignment and beam-tracking latency (Panahi, 2026).

Validation and implementation

An IoMT evidence ladder should progress from bench accuracy and communication testing through usability and workflow simulation to prospective clinical validation and post-market surveillance. Outcomes should include false-alert burden, recognition time, clinician response, adverse events, hospitalization, patient-reported outcomes, equity, cost, maintenance, cybersecurity resilience, and environmental impact. Recent studies show feasibility and selected benefits, but heterogeneity prevents a general claim that all IoMT improves outcomes (Lu et al., 2024; Nguyen et al., 2026; Patel et al., 2023; Wettstein et al., 2024).

Organizations should define the clinical objective and responder; inventory devices, software, flows, and dependencies; select connectivity and computing from hazard analysis; require interoperable data and terminology; establish secure onboarding, updating, disclosure, and decommissioning; validate local sensor/algorithm performance; exercise downtime and cyber response; and monitor drift, alert burden, inequity, and outcomes (Health Level Seven International, 2023; IEEE Standards Association, n.d.; National Institute of Standards and Technology, 2021; Torab-Miandoab et al., 2023; U.S. Food and Drug Administration, 2026).

Limitations

This is a structured narrative review, not an exhaustive systematic review. The search was broad but purposive, screening and extraction were not independently duplicated, no protocol was registered, and study-level risk of bias was not assessed with design-specific instruments. Publication and language bias are possible. The added THz evidence (Panahi, 2026) is analytical communications research and supports only a future-network reliability argument; it should not be interpreted as evidence of current clinical deployment or clinical benefit.

Future Research Priorities

Multicenter studies should compare edge, fog, cloud, and hybrid architectures under realistic failure and attack conditions; define acceptable latency and availability by clinical use case; quantify energy-security trade-offs; and evaluate semantically interoperable device-to-EHR pipelines. For beyond-5G/THz healthcare research, mobility-aware blockage, beam-training overhead, handover, tracking latency, outage, exposure constraints, and fallback connectivity should be evaluated before safety-critical use (Panahi, 2026).

AI-enabled IoMT studies should predefine calibration, subgroup performance, uncertainty, drift, alert burden, human factors, and clinical endpoints. Federated learning studies should report topology, heterogeneity, communication cost, privacy accounting, poisoning defenses, and external validation. Digital-twin studies need consensus definitions and prospective comparison with usual care. XAI studies should measure decision quality and appropriate reliance, not merely subjective trust (S. R. Abbas et al., 2024; Allen, 2024; Drummond & Gonsard, 2024; Freyer et al., 2024; Rani et al., 2023; Rosenbacke et al., 2024; Shen et al., 2024; Teo et al., 2024; van Kolschooten & van Oirschot, 2024).

Conclusion

IoMT can extend monitoring beyond the clinic and improve operational visibility, but safe value emerges only when validated sensing, dependable communication, fit-for-purpose computing, interoperable information, cybersecurity, and clinical workflow are engineered together. BLE, Wi-Fi, cellular, WBAN, edge, fog, and cloud solve different constraints; none is categorically best. THz is a future option rather than a mature healthcare solution, and its highly directional mobile links require explicit treatment of beam misalignment and tracking latency (Panahi, 2026).

The most defensible near-term strategy is a risk-based hybrid architecture with local resilience, standards-based exchange, lifecycle security, explicit alert governance, and prospective clinical evaluation. Federated learning and explainable AI are translational, while patient digital twins remain largely preclinical. Readiness claims should follow demonstrated clinical maturity, regulatory evidence, and sustained post-deployment performance. Appendix A

Declarations

Funding: No external funding was reported.

Conflicts of interest: The author declares no conflict of interest.

Protocol and registration: No protocol was registered because this work is a structured narrative review rather than a systematic review.

Data availability: No new patient-level dataset was generated. Search concepts, eligibility criteria, evidence tables, and cited sources are reported in the manuscript.

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