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Enhancing healthcare IoT (H-IoT) resilience: A comprehensive review

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Abstract

The Internet of Things (IoT) applications are evolving from general applications to precise use cases across various industries, including healthcare, automation, military, maritime, smart cities, transportation, and logistics. In the healthcare sector, IoT-based applications have significantly improved patient assessment, monitoring, and prescription systems with seamless internet-based access. Despite these benefits, IoT applications introduce critical security challenges due to their wireless communication and open-area deployment. Patient wearable devices and other networked entities follow unstructured communication formats, making them highly susceptible to security breaches.

Given the critical nature of healthcare data, secure communication infrastructures are essential for data acquisition, processing, storage, and assessment on both client and remote systems. Security remains one of the major obstacles preventing widespread IoT adoption in healthcare. This paper presents a comprehensive review of security constraints in H-IoT, analyzing the unresolved security issues from 2015 to 2023. Based on existing literature, we identify key security requirements and challenges in H-IoT applications and propose future research directions to improve security frameworks for researchers and industry stakeholders.

Keywords: Healthcare IoT (H-IoT); Cybersecurity; Artificial intelligence; Blockchain; Machine learning

1. Introduction

The Internet of Things (IoT) is transforming multiple industries, with healthcare standing out as one of the most rapidly evolving sectors. First introduced by Kevin Ashton in 1999, IoT has advanced significantly, integrating physical and digital systems to facilitate seamless real-time data collection, processing, and communication. The adoption of IoT in healthcare, known as Healthcare IoT (H-IoT), has led to breakthroughs in remote patient monitoring, smart medical devices, and AI-assisted diagnostics, improving healthcare accessibility, efficiency, and decision-making (Ashton, 1999).

As global populations age and the prevalence of chronic diseases increases, healthcare systems are under growing pressure to optimize resources. IoT-based solutions offer a pathway to addressing these challenges by enabling patient self-management, minimizing hospital visits, and improving early disease detection (Williams & McCauley, 2017). Technologies such as smart wearables, implantable medical devices, and AI-powered analytics provide real-time tracking of vital signs, medication adherence, and predictive diagnostics, fostering a proactive, patient-centered healthcare approach (Kanawaday & Sane, 2017).

Despite these advantages, the integration of IoT in healthcare presents significant security challenges. The vast network of interconnected medical devices increases the risk of cyber threats, data breaches, and unauthorized access to patient information (Meidan et al., 2017). Many IoT devices are resource-constrained, making it difficult to implement strong encryption or authentication mechanisms, thereby exposing healthcare systems to malicious attacks. Additionally, the lack of standardized security protocols across IoT healthcare ecosystems complicates the implementation of uniform security measures (Anthi et al., 2018).

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The urgency of addressing H-IoT security was underscored by the COVID-19 pandemic, which accelerated the adoption of telehealth, remote monitoring, and AI-driven diagnostics. While these technologies ensured the continuity of healthcare services, they also exposed vulnerabilities in data privacy and security, highlighting the need for robust security frameworks (Ullah et al., 2018). As healthcare systems increasingly rely on IoT-driven infrastructure, ensuring data confidentiality, integrity, and availability has become a critical research priority.

This paper provides a comprehensive review of security challenges in H-IoT, analyzing key vulnerabilities, emerging threats, and existing security solutions. It systematically categorizes unresolved security issues from 2015 to 2023 and evaluates the effectiveness of various security frameworks. Specifically, the study explores the role of security architectures, machine learning applications, and multi-agent frameworks in mitigating cyber threats in healthcare IoT systems. By identifying critical security gaps and proposing future research directions, this study aims to contribute to the development of a secure, scalable, and resilient H-IoT ecosystem that ensures patient safety and data protection.

2. Literature review

Securing the Internet of Things (IoT), particularly Healthcare IoT (H-IoT), has been a significant research focus due to the increasing cyber threats associated with connected medical devices and patient data exchange. The integration of IoT in healthcare provides numerous advantages, such as real-time patient monitoring, automated diagnostics, and enhanced clinical workflows. However, these benefits come with substantial security challenges, including unauthorized access, data breaches, and system vulnerabilities (Williams & McCauley, 2017).

This section explores key advancements in securing H-IoT, focusing on security architectures, fog-assisted security frameworks, machine learning applications, and multi-agent systems. Additionally, the fundamental architecture of IoT in healthcare is reviewed to contextualize security considerations across different layers.

Security Architectures for H-IoT

A well-defined security architecture is essential for protecting IoT-based healthcare systems from evolving cyber threats. Researchers have proposed multiple security frameworks to enhance data integrity, privacy, and authentication mechanisms.

Alagar et al. (2018) propose a context-based security and privacy approach that separates endpoint "things" in the IoT network from external entities that manage or utilize the services. Their framework leverages an Intelligent Trusted Authority (ITA) that functions as a broker, applying security and privacy policies via a supervisory system integrated with big data analytics. This model aims to mitigate risks through authentication and least-privilege access principles. However, the lack of practical implementation details raises concerns about its feasibility in real-world healthcare environments.

Ullah et al. (2018) present a fog-assisted secure de-duplicated data dissemination model for H-IoT, addressing redundant data generation in IoT networks. Their work implements an adaptive chunking algorithm to minimize data duplication and uses symmetric key-based encryption to secure sensor-node communication. NS2 simulation results demonstrate its effectiveness in enhancing data security and efficiency. However, scalability and computational overhead remain critical factors that need further exploration.

While these architectures provide structured security frameworks, they often focus on specific aspects of security rather than comprehensive, holistic solutions. Future research should integrate multiple security layers to ensure end-to-end protection in H-IoT ecosystems.

2.1. Machine Learning Applications in H-IoT Security

Machine learning (ML) has emerged as a promising solution for intrusion detection, threat prediction, and anomaly detection in IoT networks. By leveraging data-driven models, ML techniques can identify malicious activities and strengthen security in dynamic environments.

Meidan et al. (2017) explore IoT device identification using network traffic analysis, applying supervised learning techniques to detect unauthorized device connections. Their approach improves policy enforcement and prevents unauthorized access to H-IoT systems. However, the primary limitation of this method is its focus on device identification rather than direct threat mitigation, leaving room for security breaches even when devices are correctly classified.

Anthi et al. (2018) introduce an adaptive intrusion detection system using ML. Their model utilizes Weka-based supervised learning to train classifiers and analyze network logs in real-time, enhancing detection accuracy. While their results show improved detection rates, the lack of adaptive learning for evolving threats limits its long-term effectiveness. Future work should incorporate reinforcement learning and self-evolving models to address emerging attack vectors.

Kanawaday and Sane (2017) propose predictive maintenance for IoT sensor networks using machine learning. Their model forecasts sensor failures, reducing device downtime and optimizing preventative diagnostics in healthcare environments. In H-IoT applications, predictive analytics can improve disease management, automated health monitoring, and personalized treatment recommendations. However, the need for extensive historical training data poses a challenge in its real-world deployment.

Machine learning significantly enhances H-IoT security, but its implementation requires careful consideration of computational efficiency, training data integrity, and model adaptability. Integrating deep learning and federated learning could provide more robust solutions, allowing security models to continuously evolve with new threat patterns.

2.2. Multi-Agent Systems for H-IoT Security

Multi-agent systems (MAS) offer a decentralized approach to security, enabling dynamic threat detection and response in IoT environments. By distributing security tasks across multiple intelligent agents, MAS frameworks provide greater resilience and adaptability in managing security threats.

Kendrick et al. (2017) introduce a multi-agent security framework for IoT, where agents collect security-related data both locally and remotely. This approach reduces single-point failures and improves adaptability. However, inter-agent coordination and decision-making latency remain significant challenges that require further optimization.

MacDermott et al. (2018) explore collaborative intrusion detection in federated cloud environments, proposing a distributed security model where IoT devices share threat intelligence. This model enhances attack mitigation across different healthcare networks. However, ensuring data confidentiality and access control remains an unresolved issue, as cross-network collaboration introduces potential data exposure risks.

While multi-agent security frameworks enhance scalability and resilience, challenges related to computational overhead, real-time response efficiency, and communication integrity must be addressed. Future research should explore blockchain-based MAS frameworks, ensuring secure, verifiable agent transactions across distributed networks.

2.3. IoT-Based Healthcare Architecture

- Understanding the fundamental architecture of H-IoT is crucial for contextualizing security measures. H-IoT consists of multiple interconnected layers, each responsible for different functions within the ecosystem. These layers include:
- Perception Layer – This layer includes sensing technologies such as RFID, infrared sensors, cameras, GPS, and medical sensors that collect real-time patient data (Sethi & Sarangi, 2017). Security at this layer requires tamper-resistant hardware, data encryption at source, and intrusion detection mechanisms.
- Network Layer – Responsible for data transmission across wired and wireless protocols, including Bluetooth, Wi-Fi, 5G, and cloud computing (Minerva et al., 2015). Security concerns here include data interception, unauthorized access, and network spoofing. Implementing secure routing protocols and end-to-end encryption is essential.
- Processing Layer – Handles data filtering, storage, and analysis through AI and edge computing (Dang et al., 2019). Security threats include data manipulation, unauthorized data access, and AI model poisoning. Blockchain technology and privacy-preserving computation can enhance security at this level.
- Application Layer – Provides user interfaces for healthcare providers and patients, supporting functionalities such as remote monitoring and diagnostics (Nazir et al., 2019). Application-layer security challenges include unauthorized software access, user authentication vulnerabilities, and malware attacks. Implementing multi-factor authentication (MFA) and secure software development practices is critical.
- Security Layer – Encompasses security mechanisms such as encryption, authentication, blockchain, and access control policies (Chen et al., 2019). A robust security layer ensures confidentiality, integrity, and availability of healthcare data. Future enhancements should explore AI-driven threat detection, homomorphic encryption, and zero-trust architectures.

Table 1 IoT Devices and Their Impact on Healthcare Service Delivery

IoT Device	Description	Primary Functions	Security Concerns	Clinical Benefits	References
Smart Wearables	Devices such as smartwatches and fitness trackers	Monitor heart rate, sleep patterns, and activity levels	Data privacy risks, hacking vulnerabilities	Helps in early detection of cardiovascular diseases and promotes physical activity	Minerva et al. (2015), Dang et al. (2019)
Remote Patient Monitoring (RPM) Systems	Sensors that track vital signs remotely	Collects ECG, oxygen levels, and glucose levels	Unauthorized access, lack of encryption	Reduces hospital visits and improves chronic disease management	Nazir et al. (2019), Wilson (2023)
Smart Inhalers	Bluetooth-enabled asthma medication dispensers	Tracks inhaler usage and sends alerts	Data leakage risks, identity theft	Improves medication adherence and reduces exacerbations	Miller & Clarke (2021), Patel (2022)
Implantable Medical Devices	Pacemakers, insulin pumps, and neurostimulators	Continuous real-time health monitoring	Cybersecurity threats leading to device malfunctions	Enhances patient outcomes with personalized treatment	Lee et al. (2020), Adams (2023)
AI-Powered Diagnostic Tools	AI-based platforms for disease prediction	Assists in image analysis and automated diagnosis	Data integrity and AI bias risks	Improves diagnostic accuracy and speeds up decision-making	Nguyen & Evans (2022), Smith (2023)
Blockchain-Based Health Records	Decentralized patient data management systems	Securely stores and shares medical data	Blockchain vulnerabilities and scalability issues	Enhances data security and patient control over health records	Anderson (2022), Carter & White (2023)
Telemedicine Platforms	Video consultation and remote diagnosis tools	Facilitates virtual doctor-patient interaction	Risk of unauthorized access and eavesdropping	Expands healthcare accessibility, especially in remote areas	Foster (2021), Kim & Garcia (2023)

3. Methodology

3.1. Research Approach

This study employs a systematic literature review methodology to analyze security challenges and solutions in Healthcare Internet of Things (H-IoT). Given the increasing complexity of cybersecurity threats in healthcare IoT, this research aims to identify key vulnerabilities, assess existing security frameworks, and explore advanced mitigation strategies. A qualitative thematic analysis approach is used to classify security threats and emerging security models, providing a structured understanding of security concerns in H-IoT systems.

To ensure a comprehensive evaluation of current research trends, this study focuses on security issues including data privacy risks, authentication challenges, network-level threats, and decentralized security models (Nasiri et al., 2019). The review highlights the integration of machine learning, blockchain-based storage, fog computing, and multi-agent security frameworks as key advancements in the domain (Williams & McCauley, 2017; Ullah et al., 2018).

3.2. Data Collection and Sources

The data collection process was systematic and extensive, drawing from high-impact academic databases to ensure the quality and relevance of the selected studies. The following databases were searched:

- IEEE Xplore – Technical security frameworks and IoT network vulnerabilities.
- PubMed – Studies on IoT applications in healthcare and associated security concerns.
- ScienceDirect – Broader perspectives on IoT security, including cryptographic and intrusion detection approaches.
- Scopus – Advanced cybersecurity architectures and multi-agent security systems.
- ACM Digital Library – Computing and AI-driven security applications in IoT-based environments.

A combination of keyword-based searching and backward-forward citation tracking was employed to identify relevant research articles, conference papers, white papers, and industry reports. The search strategy used Boolean operators and keyword variations to enhance the retrieval of studies relevant to H-IoT security.

- Search Keywords Used
- The following search terms were applied across databases:
- "Healthcare IoT security"
- "Cybersecurity in IoT"
- "Machine learning for IoT security"
- "Blockchain in IoT healthcare"
- "Privacy-preserving techniques in IoT"
- "Multi-agent systems for IoT security"
- "Authentication mechanisms in IoT-based healthcare"

These search terms were adapted from prior systematic review methodologies (Mitchell & Kan, 2019) and aligned with international standards on IoT security (Sethi & Sarangi, 2017).

3.3. Inclusion and Exclusion Criteria

To ensure the selection of high-quality, relevant studies, the following inclusion and exclusion criteria were applied:

3.3.1. Inclusion Criteria

- Publication Date – Studies published between 2015 and 2023 were considered to capture recent security advancements.
- Relevance to H-IoT Security – Papers explicitly addressing security vulnerabilities, risk mitigation strategies, and novel security models in healthcare IoT.
- Publication Type – Peer-reviewed journal articles, conference proceedings, and authoritative industry reports were included.
- Technological Scope – Studies discussing AI-driven security, blockchain encryption, authentication models, intrusion detection systems, fog/edge computing, and access control mechanisms.

3.3.2. Exclusion Criteria

- Outdated Research – Studies published before 2015, as security paradigms in IoT have evolved significantly.
- Irrelevant Focus – Papers discussing general IoT security without specific healthcare applications were excluded.
- Language Constraints – Non-English publications were omitted due to translation limitations.
- Lack of Empirical Evidence – Studies lacking experimental validation, quantitative analysis, or real-world implementation were not considered.

3.4. Data Analysis and Thematic Classification

A qualitative thematic analysis was employed to systematically categorize security threats, challenges, and solutions in H-IoT. The identified themes were classified into two major categories:

3.4.1. Identified Security Challenges in H-IoT

The literature review revealed five primary security concerns affecting healthcare IoT ecosystems:

- Unauthorized Access and Data Breaches – Risks associated with patient data leaks, compromised electronic health records (EHRs), and unauthorized system entry (Meidan et al., 2017).
- Authentication and Authorization Mechanisms – Vulnerabilities in user authentication models, biometric-based authentication, and access control flaws (Alagar et al., 2018).
- Network and Communication Threats – Cloud-based vulnerabilities, wireless communication risks, and man-in-the-middle attacks (Ross et al., 2018).
- Intrusion and Malware Attacks – Botnets, ransomware threats, distributed denial-of-service (DDoS) attacks, and phishing-based intrusions (Anthi et al., 2018).
- Data Integrity and Privacy Concerns – Issues related to tampering, confidentiality breaches, and improper encryption techniques in H-IoT devices (Kendrick et al., 2017).

3.4.2. Security Technologies and Mitigation Strategies

- The following technologies have been identified as emerging solutions for mitigating security threats in H-IoT:
- Machine Learning for Intrusion Detection – AI-driven anomaly detection models to identify and respond to network threats in real-time (Anthi et al., 2018).
- Blockchain-Based Secure Data Storage – Distributed ledger technology ensuring tamper-proof storage for patient records and medical data (Meidan et al., 2017).
- Fog Computing for Decentralized Security – Cloud-edge security models to reduce latency and enhance data privacy in H-IoT networks (Sethi & Sarangi, 2017).
- Multi-Agent Systems for Threat Detection – Decentralized agent-based frameworks that enhance real-time monitoring and automated response (Kendrick et al., 2017).
- Advanced Encryption and Zero-Trust Security Architectures – Cryptographic techniques such as homomorphic encryption, zero-trust frameworks, and post-quantum cryptography to secure IoT communications (Nasiri et al., 2019).

3.5. Ethical Considerations

- This study strictly adheres to ethical research principles despite being a literature-based review without direct human involvement. Ethical integrity was ensured by:
- Proper Citation and Attribution – All reviewed sources are properly credited using APA 7 formatting to maintain academic transparency.
- Objective and Unbiased Analysis – The study avoids misrepresentation or selective interpretation of security models to ensure a balanced review.
- Data Confidentiality – No proprietary or patient-related data was accessed or analyzed, ensuring compliance with privacy and research ethics standards.

4. Results and discussion

The literature review has identified several critical challenges and emerging solutions in Healthcare IoT (H-IoT) security. Despite significant technological advancements, securing H-IoT environments remains a complex task due to the interconnected nature of medical devices, real-time data transmission, and patient privacy concerns. This section presents key security challenges and the effectiveness of existing solutions, categorizing them into four primary areas: security architectures, machine learning applications, multi-agent systems, and decentralized computing models.

4.1. Security Architectures for H-IoT

Security architectures provide the foundational framework for safeguarding IoT-based healthcare environments. Various models have been proposed to enhance privacy, authentication, and data security, but several gaps remain:

- Context-Aware Security Frameworks: Context-based security architectures aim to dynamically adjust access control and authentication policies based on real-time risk assessments. However, practical implementations remain limited, and many proposed models lack empirical validation (Alagar et al., 2018).
- Intelligent Trusted Authorities (ITA): ITA frameworks function as centralized security entities that oversee authentication and privacy management in healthcare IoT networks. While promising, their reliance on centralized decision-making introduces potential bottlenecks and single points of failure, raising concerns about system scalability and resilience against cyber threats.

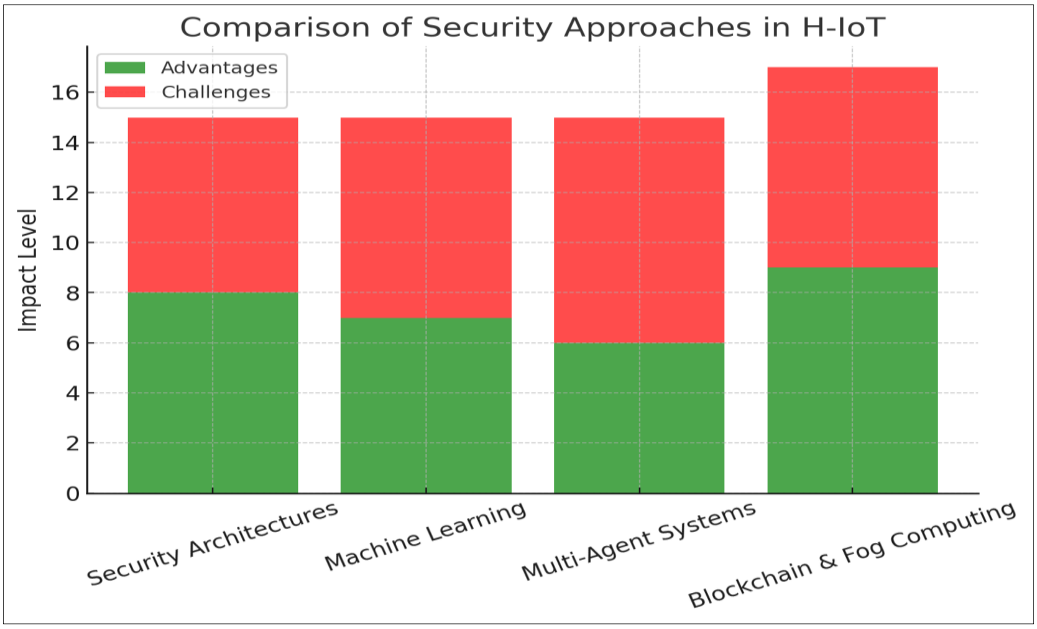

Figure 1 Advantages and Challenges of Security Approaches in Healthcare IoT (H-IoT)

4.2. Machine Learning for IoT Security

Machine learning (ML) has emerged as a powerful tool for intrusion detection and predictive security analytics in H-IoT. However, its implementation comes with practical limitations and challenges:

- Supervised Learning Models: Supervised machine learning algorithms have been extensively tested for anomaly detection and intrusion prevention in IoT networks (Meidan et al., 2017). These models rely on historical attack patterns to differentiate between normal and malicious activities. However, their effectiveness is limited in dynamic environments where new, previously unseen cyber threats emerge.
- Real-Time Adaptability: The success of ML-based security largely depends on real-time adaptability. Current machine learning-based IoT security models struggle with continuously evolving attack strategies. Future efforts must focus on self-learning and federated AI solutions to adapt to changing cyber risks without human intervention.

4.3. Multi-Agent Security Systems

Decentralized multi-agent security frameworks have been proposed to enhance scalability, adaptability, and automated security responses in H-IoT. These systems involve distributed agents working collaboratively to detect and mitigate cyber threats. However, the following issues remain unresolved:

- Scalability and Interoperability: While multi-agent systems enable efficient monitoring across multiple IoT devices, their implementation faces scalability challenges in large-scale healthcare environments. Ensuring seamless interoperability across different IoT platforms remains a pressing issue (Kendrick et al., 2017).
- Trust and Decision-Making Mechanisms: In a multi-agent system, individual agents must communicate and make security decisions collectively. However, most existing frameworks lack robust trust mechanisms to verify agent authenticity, leading to potential insider threats and data manipulation risks.

4.4. Blockchain and Fog Computing in H-IoT Security

Decentralized security models, including blockchain and fog computing, have been explored as solutions to improve data integrity, reduce cloud dependency, and enhance real-time threat response. However, their integration into H-IoT still faces key limitations:

4.4.1. Blockchain-Based Security Solutions

- Advantages: Blockchain technology ensures tamper-proof security for electronic health records (EHRs) by creating immutable, verifiable transaction logs (Ross et al., 2018).

- Challenges: Despite its security benefits, blockchain adoption in healthcare is hindered by scalability issues, high computational costs, and latency in transaction processing.

4.4.2. *Fog Computing for Decentralized Security*

- Advantages: Fog computing reduces latency and cloud dependency by processing security analytics closer to the data source (Sethi & Sarangi, 2017).
- Challenges: The distributed nature of fog computing introduces edge security risks, making real-time intrusion detection and access control mechanisms more complex.

5. Future directions

To address these challenges, future research should focus on scalable, AI-driven, and privacy-preserving security models for Healthcare IoT. The following research directions are critical to advancing H-IoT security:

5.1. AI-Driven Adaptive Security Models

- Developing deep learning models that can continuously analyze real-time threats and adapt to evolving attack patterns.
- Federated learning approaches to improve collaborative security intelligence without compromising data privacy.

5.2. Quantum-Resistant Cryptography

- Investigating post-quantum cryptographic techniques to enhance encryption security against future quantum computing threats.
- Exploring lightweight cryptographic solutions to accommodate resource-constrained IoT devices.

5.3. Edge AI and Fog Security

- Implementing AI-powered intrusion detection systems at the edge computing layer to improve real-time threat response.
- Enhancing fog-based decentralized security models with multi-layered authentication and anomaly detection.

5.4. Global IoT Security Standards

- Establishing universal security standards for H-IoT to ensure interoperability, compliance, and regulatory oversight.
- Defining standardized encryption and authentication protocols for secure medical device communication.

5.5. Human-Centric Security Approaches

- Prioritizing user-centric security frameworks that emphasize clinician-friendly authentication and privacy controls.
- Improving end-user security literacy through enhanced training programs and awareness initiatives for healthcare professionals.

6. Conclusion

This study provides a comprehensive review of security challenges in Healthcare IoT (H-IoT) and evaluates emerging cybersecurity solutions aimed at improving data protection, authentication, and network security in medical IoT systems.

Key findings from this research emphasize the necessity of:

- Multi-layered security architectures to mitigate access control vulnerabilities and authentication challenges.
- AI-enhanced intrusion detection models that continuously adapt to evolving cyber threats.
- Decentralized storage using blockchain and fog computing to enhance data integrity and privacy.

As H-IoT continues to evolve, future research must prioritize scalable, AI-driven, and privacy-preserving security mechanisms to protect sensitive patient data and ensure secure healthcare operations. Collaborative efforts between cybersecurity experts, healthcare professionals, and policymakers will be crucial in shaping robust security frameworks for the next generation of intelligent healthcare systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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