Trends in Health Informatics

www.thi.reapress.com

THI. Vol. 2, No. 2 (2025) 82–90.

Paper Type: Original Article

From Data Silos to Interoperable Ecosystems: Challenges and Solutions for EHR/HIE Integration in Digital Health

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Citation:

Received: 08 December 2024 *Revised: 17 February 2025* *Accepted: 03 April 2025*	Ghanbari, Sh. (2025). From data silos to interoperable ecosystems: Challenges and solutions for EHR/HIE integration in digital health. *Trends in health informatics, 2*(2), 82-90.

Abstract

The fragmentation of health data across diverse Electronic Health Record (EHR) systems and Health Information Exchanges (HIEs) remains a major obstacle to delivering coordinated, efficient, and data-driven care. This review provides a comprehensive overview of the current landscape of EHR/HIE integration, examining the technical, organizational, and regulatory factors that continue to hinder interoperability. It highlights three core strategies for overcoming these barriers: the adoption of standardized data models that support consistent semantic and structural representation; the use of API-driven and service-oriented architectures that enable flexible, real-time connectivity; and the application of artificial intelligence techniques for data harmonization, including cleansing, record linkage, and resolution of structural inconsistencies. Beyond technical considerations, the paper also addresses essential issues related to data governance, privacy, security, and policy frameworks that shape the implementation and sustainability of interoperable ecosystems. By synthesizing emerging approaches across these domains, the review outlines a pathway for transitioning from isolated data silos to interconnected digital health infrastructures capable of supporting scalable clinical workflows, improved decision-making, and more integrated patient care. The analysis aims to clarify both the opportunities and challenges involved in achieving meaningful interoperability in contemporary digital health environments.

Keywords: Electronic health record, Health information exchange, Data integration, Mobile health, Telemedicine, Big data, Fast healthcare interoperability resources.

1 | Introduction

The healthcare industry is undergoing a profound digital transformation, driven by advances in information technology, cloud computing, Mobile Health (mHealth), wearable devices, and telemedicine platforms [1], [2]. Despite this progress, the widespread adoption of disparate Electronic Health Record (EHR) systems has inadvertently led to the fragmentation of patient data across multiple, often incompatible, silos. These isolated

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https://doi.org/10.22105/thi.vi.34

datasets restrict clinicians' ability to obtain a complete view of patient health, thereby limiting informed decision-making, delaying interventions, and potentially compromising patient safety [3].

Fragmented data also creates challenges for researchers and public health authorities, who rely on aggregated, high-quality datasets to perform population health analyses, develop predictive models, and evaluate intervention outcomes [4]. Without interoperability, data remains underutilized, redundant testing is often necessary, and opportunities for proactive care and predictive analytics are significantly reduced. Furthermore, the lack of standardization across EHR platforms complicates integration with emerging AI and ML algorithms that require consistent, structured input to generate accurate predictions and clinical recommendations [5], [6].

The integration of EHRs with Health Information Exchanges (HIEs) represents a crucial step toward creating interoperable ecosystems. HIEs facilitate the secure sharing of structured and unstructured patient information across institutions, enabling comprehensive longitudinal health records that support continuity of care, coordinated treatment plans, and data-driven decision-making. Interoperable systems not only enhance clinical workflows but also unlock the potential for advanced AI/ML applications, including predictive analytics for early warning systems, personalized treatment recommendations, and population health management [7], [8].

Emerging solutions, such as Fast Healthcare Interoperability Resources (FHIR), Health Level Seven (HL7) standards, and API-driven platforms, are increasingly employed to bridge these silos, harmonize data formats, and allow real-time integration across disparate EHR systems [9]. Additionally, AI-powered middleware tools are being developed to automatically map, standardize, and reconcile heterogeneous datasets, enabling seamless aggregation of patient information while maintaining data security and privacy compliance [10].

Moreover, the rapid growth of digital health technologies (including mHealth applications, wearable devices, Remote Patient Monitoring (RPM), and Internet of Medical Things (IoMT) platforms) has exponentially increased the volume and complexity of healthcare data [1], [2]. While these innovations promise more continuous, patient-centered care, they also exacerbate the problem of data fragmentation when integration is insufficient. Without effective interoperability frameworks, the full potential of AI-assisted diagnostics, predictive analytics, and personalized treatment plans cannot be realized.

In addition to technical barriers, organizational and policy challenges hinder EHR/HIE integration. Variations in institutional data governance policies, privacy regulations, and cybersecurity standards create obstacles for seamless data exchange [9]. Moreover, disparities in EHR adoption, differences in data entry practices, and lack of standardized terminologies further complicate integration efforts. Addressing these challenges is critical not only for improving clinical outcomes but also for enabling large-scale research, health monitoring, and the deployment of AI/ML-driven digital health solutions across heterogeneous healthcare environments.

Overall, overcoming the challenges of fragmented patient data is essential for realizing the full benefits of digital health transformation. By integrating EHRs and HIEs into interoperable ecosystems, healthcare providers can improve clinical decision-making, enable predictive and personalized care, enhance research capabilities, and lay the foundation for next-generation telemedicine and RPM solutions [11], [12].

2|Digital Health & Telemedicine Ecosystem

Digital health incorporates a wide range of Information And Communication Technology (ICT) solutions to enhance the quality, efficiency, and accessibility of healthcare delivery [1], [2]. Core components of this ecosystem include EHRs, HIEs, mHealth applications, RPM systems, telemedicine platforms, and IoMT devices. These tools collectively facilitate real-time collection, storage, and analysis of patient data, enabling more proactive, patient-centered care models [1].

Wearable devices, including smartwatches, continuous glucose monitors, and ECG patches, provide continuous streams of physiological data such as heart rate, activity levels, oxygen saturation, and sleep patterns. By integrating these measurements with EHR and mHealth platforms, clinicians can detect early signs of clinical deterioration, intervene promptly, and tailor treatments to individual patients. Moreover, telemedicine platforms extend the reach of healthcare services to underserved or remote populations, reducing geographic and temporal barriers to care [13], [14].

Despite these advancements, the digital health ecosystem continues to face data fragmentation due to the heterogeneous nature of vendor systems, differing interoperability standards, and variable institutional adoption practices [2]. Inconsistent data structures, lack of standardized coding terminologies, and proprietary storage formats contribute to isolated silos, limiting the ability to perform comprehensive analytics or apply AI/ML-driven decision support across datasets. These challenges underscore the necessity for robust integration strategies, including standardized APIs, FHIR-compliant data exchange, and AI-assisted data harmonization tools to create a cohesive, interoperable digital health environment [5], [9], [10].

Looking ahead, the convergence of IoMT, mHealth, EHR/HIE integration, and AI/ML applications promises to transform healthcare delivery. Fully interoperable ecosystems will enable continuous monitoring, predictive modeling, personalized interventions, and real-time clinical decision support, paving the way for more resilient, efficient, and patient-centered healthcare systems [7], [8], [12].

3 | Data Silos in Healthcare & Integration Challenges

Healthcare data silos primarily emerge due to the coexistence of heterogeneous and often incompatible EHR systems, inconsistent adoption of interoperability standards, and organizational resistance to centralized data governance [2], [15]. These fragmented data repositories impede seamless access to comprehensive patient information, thereby compromising patient safety, delaying timely interventions, and increasing the likelihood of redundant diagnostic testing. Furthermore, the presence of isolated silos limits the effective application of advanced analytics, AI, and machine learning tools that rely on large, high-quality datasets for accurate predictive modeling and decision support [5], [6].

The technical and organizational challenges associated with data silos are multifaceted. Semantic heterogeneity arises when different EHR vendors or institutions use diverse terminologies, coding systems, or clinical taxonomies, preventing straightforward data aggregation and interpretation. Differing data formats, including structured and unstructured records, further complicate the integration process, necessitating mapping, normalization, and reconciliation efforts to achieve interoperability [9]. Additionally, governance and policy issues, such as institutional policies on data sharing, privacy regulations, and cybersecurity requirements, can inhibit cross-institutional data exchange and limit access to longitudinal patient information.

Addressing these challenges is critical to realizing the full potential of digital health ecosystems. Strategies such as adopting standardized data formats, leveraging FHIR, implementing HL7 standards, and utilizing AI-assisted middleware for data harmonization have shown promise in bridging silos and facilitating seamless integration across heterogeneous systems [8], [10]. *Table 1* summarizes the key challenges associated with healthcare data silos and highlights their implications for patient care, analytics, and AI/ML deployment.

Table 1. Key challenges associated with healthcare data silos.

Challenge	Description	Implications for Patient Care and Analytics
Semantic heterogeneity	Use of different terminologies, coding systems, and clinical taxonomies across EHR systems and institutions	Limits data aggregation, complicates AI/ML model training, may lead to inconsistent clinical decisions
Differing data formats	Presence of structured, semi-structured, and unstructured data across systems	Requires mapping, normalization, and reconciliation; delays integration and real-time analytics
Incompatible EHR systems	Vendor-specific software and proprietary storage structures	Creates isolated silos; restricts seamless access to longitudinal patient records
Governance & policy issues	Institutional policies, privacy regulations, and cybersecurity requirements	Hinders cross-institutional data exchange; may delay timely interventions and restrict research opportunities
Organizational resistance	Lack of stakeholder engagement, resistance to change, or insufficient IT infrastructure	Slows adoption of interoperable solutions; limits effectiveness of AI-assisted decision support
Data redundancy & inconsistency	Duplicate records or conflicting patient information across systems	Increases risk of diagnostic errors and unnecessary tests; reduces trust in data quality

4 | Solutions and Standards for Interoperability

Achieving true interoperability within digital health ecosystems requires a multilayered strategy that integrates technical standards, data governance frameworks, and intelligent harmonization mechanisms. Internationally recognized standards, particularly HL7 FHIR, Clinical Document Architecture (CDA), and open API frameworks, serve as the foundational enablers for structured and semantically consistent data exchange across heterogeneous HER platforms and HIEs. Unlike earlier standards, FHIR provides modular, resource-based data models and RESTful APIs that support real-time communication, scalability, and broader adoption across clinical, administrative, and mHealth applications.

Beyond standardization, AI/ML-driven middleware has emerged as a transformative layer capable of resolving semantic heterogeneity and integrating multimodal datasets from EHRs, wearables, RPM systems, and IoMT devices. These middleware architectures utilize machine learning techniques, such as ontology alignment, Natural Language Understanding (NLU), and automated data mapping, to harmonize clinical terminologies (e.g., SNOMED CT, LOINC, ICD-10) and unify dispersed patient information into consolidated longitudinal health records [5]. This unified data infrastructure facilitates advanced analytics, supports clinical decision-support systems, and enables the deployment of predictive and personalized care models.

Interoperability also relies heavily on open, vendor-agnostic ecosystem design, allowing third-party developers to integrate digital therapeutics, telemedicine modules, and population health analytics tools into existing infrastructures. Cloud-native architectures further enhance this flexibility by offering scalable storage, federated learning capabilities, and secure data-sharing protocols that comply with privacy regulations. Blockchain-based governance models are also gaining traction for ensuring immutable audit trails, consent management, and trust across decentralized healthcare networks.

Fig. 1 illustrates a conceptual framework in which standardized data models, AI-powered integration services, and secure exchange protocols collectively form a layered interoperable ecosystem. This architecture not only ensures seamless data flow across organizational boundaries but also strengthens the foundation for next-generation digital health innovations.

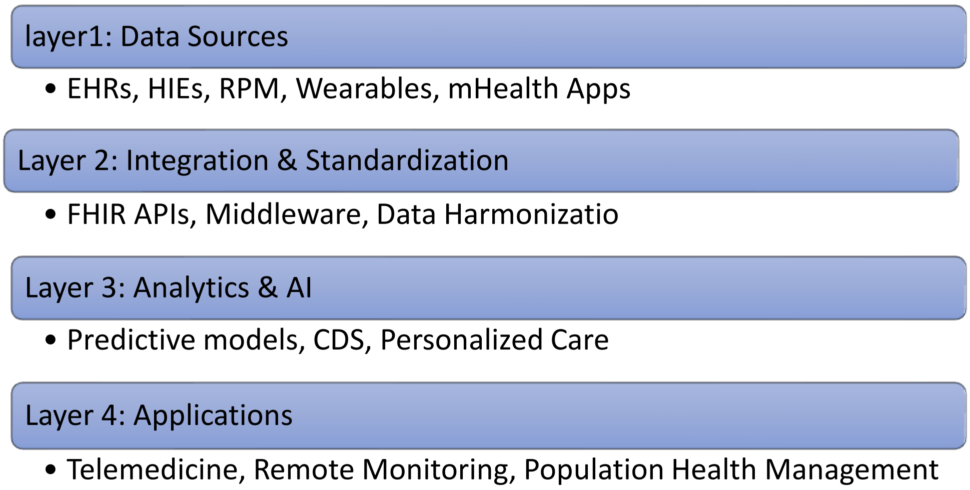

Fig. 1. Conceptual framework illustrating the four-layer architecture enabling interoperability, AI-driven analytics, and integrated digital health applications.

5 | AI/ML Applications for EHR/HIE Integration

The integration of EHRs and HIEs is increasingly being facilitated by advanced AI/ML techniques that address long-standing challenges of data heterogeneity, incompleteness, and semantic inconsistency across healthcare systems. AI-driven interoperability solutions enable not only the technical alignment of datasets but also the meaningful interpretation of clinical information in ways that conventional rule-based systems cannot achieve.

First, AI/ML algorithms are capable of mapping and harmonizing heterogeneous datasets originating from multiple EHR vendors, clinical coding systems, and institutional workflows. Through techniques such as ontology alignment, embedding-based semantic matching, and automated terminology mapping, machine learning supports the unification of disparate clinical vocabularies (e.g., ICD-10, SNOMED-CT, LOINC). These models improve data consistency across systems, enabling seamless aggregation and exchange of clinical records [6].

Second, ML models can predict missing values, detect anomalies, and resolve inconsistencies in clinical records. Techniques like deep imputation networks, generative models, and probabilistic graphical models allow the reconstruction of incomplete laboratory, medication, and vital-sign data, significantly improving data quality for downstream analytics. Automated error detection and deduplication further reduce documentation discrepancies that commonly arise during cross-system data exchange [5].

Third, AI-enabled interoperability platforms facilitate real-time clinical decision-making by integrating streams of structured EHR data, RPM signals, imaging results, and patient-reported outcomes into unified dashboards. These systems support clinicians by generating personalized risk predictions, triage recommendations, and clinical alerts during virtual care encounters; enhancing diagnostic accuracy and continuity of care.

Finally, the harmonized data environment created by AI-enhanced integration unlocks large-scale population health analytics, early warning systems, and precision medicine applications. Unified datasets form the foundation for advanced predictive models used to forecast disease outbreaks, identify high-risk patient cohorts, and support targeted interventions for chronic disease management [7]. This level of analytics is only possible when AI resolves fragmentation issues and enables cross-institutional data liquidity.

Overall, AI and ML serve as critical enablers of next-generation interoperable digital health ecosystems, transforming isolated clinical repositories into integrated infrastructures capable of supporting real-time analytics, research, and personalized care delivery.

6 | Privacy, Security, and Policy Considerations

Ensuring the privacy and security of integrated healthcare data remains one of the most critical challenges in advancing interoperable EHR/HIE ecosystems. As healthcare organizations move toward large-scale data integration, the attack surface expands significantly, increasing the risk of data breaches, unauthorized access, and cyberattacks [9]. To safeguard sensitive clinical information, robust technical controls, including end-to-end encryption, multi-factor authentication, Role-Based Access Control (RBAC), intrusion detection systems, and continuous audit logging, must be implemented across the entire data lifecycle. These mechanisms ensure that only authorized stakeholders can access Protected Health Information (PHI) while maintaining a detailed audit trail to support accountability and forensic investigations.

Beyond technical protections, regulatory compliance forms the backbone of trustworthy HIE. Healthcare institutions must adhere to local and international data protection laws, such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States, the General Data Protection Regulation (GDPR) in the European Union, and regional policies governing data residency and patient consent. These regulations impose strict requirements on data minimization, breach notification, consent management, and patient rights, ensuring that interoperability initiatives do not compromise privacy or ethical obligations. The complexity of cross-jurisdictional data exchange poses additional challenges, particularly in multinational telehealth and cloud-based digital health services, where differing legal frameworks must be simultaneously satisfied [9].

Emerging technologies such as blockchain and distributed ledger systems offer innovative solutions for secure and verifiable data exchange within interoperable digital health networks. Blockchain provides immutable audit trails, decentralized authorization, and cryptographically secured transactions, reducing opportunities for tampering or unauthorized modification of clinical records. Smart contracts can automate consent management and access permissions, ensuring that data sharing complies with predefined policies while enhancing transparency and patient control [10]. Hybrid models that combine blockchain with off-chain storage and federated learning, further enable secure analytics without requiring centralized data pooling, balancing privacy protection with advanced AI-driven insights.

Overall, addressing privacy, security, and policy considerations is essential to building trust in integrated digital health ecosystems. Without rigorous protections and clear governance frameworks, interoperability initiatives risk undermining patient confidence, limiting data sharing, and constraining the adoption of AI-driven healthcare innovations. Properly designed security architectures and regulatory, compliance mechanisms therefore serve as foundational pillars for sustainable, scalable, and ethically responsible digital transformation in healthcare.

7 | Emerging Trends and Practical Implementation

Recent advancements in digital health infrastructure have accelerated the transition toward more interoperable and patient-centered data ecosystems. One of the most prominent trends is the rapid adoption of cloud-based EHR platforms, which provide scalable storage, real-time data accessibility, and seamless integration with third-party applications and analytics engines. Cloud-native architectures allow healthcare organizations to break free from the limitations of siloed on-premises systems, enabling dynamic data exchange, streamlined updates, and enhanced disaster recovery capabilities [15]. These platforms also support advanced interoperability frameworks built around FHIR standards and API-driven data sharing models, promoting richer connectivity between hospitals, clinics, laboratories, and telemedicine services.

Another emerging trend is the deployment of AI-powered middleware solutions. These systems function as intelligent integration layers capable of harmonizing heterogeneous datasets originating from multiple EHR vendors, HIEs, wearable devices, and IoT-based monitoring platforms. By applying machine learning algorithms for entity matching, semantic mapping, and anomaly detection, AI middleware enhances data quality and reduces manual effort associated with data cleaning and reconciliation. This facilitates the creation of unified patient longitudinal records, which in turn strengthens predictive analytics, clinical decision support, and population health management initiatives [5], [6].

In parallel, healthcare systems are increasingly shifting toward patient-centered interoperability models, where patients control access permissions and contribute directly to their health records via mHealth applications and personal health devices. This trend supports shared decision-making, improves patient engagement, and broadens the scope of datasets available for precision medicine. Hospitals implementing these models report lower diagnostic redundancies, improved continuity of care, and enhanced research capabilities due to more comprehensive and timely data availability [11].

Despite these advancements, the pathway to practical implementation remains complex. Key challenges include high transition costs, especially for small and resource-limited facilities; legacy system constraints that inhibit integration with modern APIs; and interoperability gaps caused by proprietary vendor architectures. Additionally, the healthcare workforce often requires specialized training to adapt to new workflows, embrace new technologies, and manage AI-enhanced applications effectively [16]. Resistance to organizational change and insufficient technical capacity can further delay implementation timelines.

Achieving successful and sustainable interoperability depends on establishing strong governance structures, engaging multidisciplinary stakeholders, including clinicians, IT teams, policy makers, and patients and maintaining continuous monitoring and evaluation processes. Institutions that prioritize iterative improvement, transparent communication, and data-driven planning are more likely to realize the full benefits of interoperable digital health ecosystems, including improved patient outcomes, operational efficiency, and innovation capacity.

8 | Conclusion

The ongoing transition from fragmented data silos toward fully interoperable digital health ecosystems represents a foundational shift in modern healthcare delivery. Fragmentation of patient information across multiple EHRs and HIEs has historically impeded clinical decision-making, reduced care continuity, and limited the potential for large-scale analytics. By adopting standardized protocols, including HL7 FHIR, CDA, and open APIs, healthcare organizations can establish a common framework for data exchange, ensuring semantic consistency and structural compatibility across heterogeneous systems.

AI and ML technologies serve as the cognitive layer that enables seamless data integration, automated harmonization, and real-time interpretation of complex multimodal datasets. These capabilities facilitate predictive analytics, early warning systems, personalized medicine, and intelligent clinical decision support, transforming previously isolated data repositories into actionable knowledge. The integration of secure, privacy-preserving mechanisms, including encryption, access control, audit logging, and emerging blockchain-based models, further ensures that interoperable systems maintain patient trust and regulatory compliance.

Practical implementation of interoperable infrastructures requires attention to governance, workforce training, stakeholder engagement, and continuous evaluation. Institutions that adopt cloud-based platforms, AI-powered middleware, and patient-centered interoperability models report tangible improvements in clinical outcomes, reduced redundancies, enhanced research capabilities, and optimized telemedicine delivery.

In conclusion, the convergence of standardized data protocols, advanced AI/ML integration, and robust security frameworks creates the foundation for scalable, efficient, and equitable healthcare systems. Ongoing research, policy development, and collaborative implementation strategies will be pivotal to fully realizing the transformative potential of interoperable EHR/HIE ecosystems, ultimately enabling more coordinated, predictive, and patient-centered care across healthcare networks worldwide.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability

All data are included in the text.

Conflicts of Interest

The authors declare no conflict of interest.

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