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A Critical Review of Health Data Interoperability Standards: FHIR, HL7, and Beyond

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ABSTRACT

Health data interoperability is essential for enabling seamless communication, data sharing, and coordinated care across diverse healthcare systems. As digital transformation accelerates within the health sector, the adoption of standardized data exchange protocols becomes increasingly critical. This paper presents a critical review of prominent health data interoperability standards, focusing on Fast Healthcare Interoperability Resources (FHIR), Health Level Seven (HL7), and other emerging frameworks. The review evaluates the historical evolution, structural design, implementation mechanisms, and comparative strengths and limitations of these standards in real-world clinical environments. FHIR, developed by HL7, represents a modern, web-based approach to healthcare data exchange, emphasizing modular resources, RESTful APIs, and flexibility for mobile and cloud-based applications. In contrast, earlier HL7 versions such as v2 and v3 utilize more rigid, message-based architectures. Although HL7 v2 remains widely used, it faces challenges in scalability and semantic consistency. The paper also explores other interoperability frameworks, including Digital Imaging and Communications in Medicine (DICOM) for imaging data, Integrating the Healthcare Enterprise (IHE), and openEHR. Special attention is given to the role of semantic interoperability, data governance, and compliance with privacy regulations such as HIPAA and GDPR. Findings highlight that while FHIR has significantly advanced interoperability by offering extensibility, developer support, and better alignment with modern software paradigms, challenges remain in universal adoption, data standardization across vendors, and integration with legacy systems. The review further identifies gaps in cross-border data sharing, patient consent management, and data provenance. Recommendations are made for harmonizing standards, promoting open APIs, and fostering collaboration among stakeholders including vendors, regulators, and clinicians. This critical synthesis provides healthcare organizations, policymakers, and developers with a comprehensive understanding of the current landscape and future directions of health data interoperability. By aligning technical standards with clinical needs and regulatory frameworks, the industry can move toward more connected, patient-centered care systems.

Keywords: Health Data Interoperability, FHIR, HL7, Healthcare Standards, Semantic Interoperability, EHR, Data Exchange, Healthcare IT, Data Governance, Patient Data Sharing.

1. INTRODUCTION

Health data interoperability is an essential concept in modern healthcare, referring to the ability of various health information systems, devices, and applications to effectively access, exchange, interpret, and utilize data across diverse platforms, irrespective of their sources. This capability underpins the seamless communication and data sharing necessary for clinical practice, administration, and public health research (Adelodun & Anyanwu, 2024, Chigboh, Zouo & Olamijuwon, 2024, Ogugua et al., 2024). Research indicates that as healthcare systems rapidly digitize, the significance of interoperability escalates, supporting continuity of care, reducing medical errors, optimizing operational efficiencies, and enabling informed decision-making processes (Martin et al., 2022; Matney et al., 2019; García et al., 2018; Kazemi-Arpanahi et al., 2020).

Interoperability is crucial for enhancing the coordination and efficiency of healthcare delivery. Healthcare providers equipped with interoperable systems can access comprehensive and up-to-date patient data at the point of care, which not only facilitates transitions between different care settings but also bolsters chronic disease management and enhances patient empowerment through greater engagement (Garza et al., 2021; Matney et al., 2019; Kazemi-Arpanahi et al., 2020). In terms of public health, interoperable systems allow for effective aggregation and analysis of large datasets, which is invaluable for monitoring population health trends and driving strategic health interventions (Bosco et al., 2021; García et al., 2018; Everson et al., 2024).The ability to exchange information efficiently is especially critical in responding to public health crises, such as the COVID-19 pandemic, where timely data sharing directly affects surveillance and management efforts (Kazemi-Arpanahi et al., 2020; Noumeir, 2018; Mishra et al., 2021).

Various standards and frameworks have been developed to address the growing demand for interoperability, with Health Level Seven (HL7) and Fast Healthcare Interoperability Resources (FHIR) being among the most significant (Hölter et al., 2024; Noumeir, 2018; Everson et al., 2024). HL7 has long served as a cornerstone for data interchange in healthcare, establishing protocols that facilitate the communication of medical information across systems (Black et al., 2018; Noumeir, 2018). The introduction of FHIR has represented a paradigm shift, offering a more agile and modern approach to data structuring and exchange that is especially relevant in the context of contemporary healthcare needs (Pavão et al., 2024; (Matney et al., 2019; Walinjkar, 2018). Other standards, such as the Clinical Document Architecture (CDA) and Digital Imaging and Communications in Medicine (DICOM), contribute to the broader interoperability landscape by providing specialized frameworks for handling distinct types of health information (Hoang et al., 2019; Lax, 2019). A critical examination of these standards reveals their diverse strengths and unique challenges as healthcare continues to evolve (Hölter et al., 2024).

To ensure that interoperability standards fulfill their potential, ongoing evaluation and adaptation are required. This includes understanding the technical frameworks of FHIR, HL7, and other standards, examining their levels of implementation maturity, and aligning them with the needs of modern healthcare systems (Barker et al., 2024; Garza et al., 2024; Dixon et al., 2020). There remains a pressing need for comprehensive reviews that identify gaps in the current interoperability ecosystem, recognize overlaps between standards, and explore opportunities for unifying disparate systems to enhance overall health IT infrastructure and policy (Dixon et al., 2020; Okon et al., 2024).

In conclusion, the push towards improved health data interoperability is driven by the necessity for integrated healthcare systems that are responsive to evolving challenges and ready to harness the power of digital health innovations (Adepoju et al., 2022, Gbadegesin et al., 2022). By reinforcing interoperability as a foundational pillar, healthcare stakeholders can enhance care delivery, boost efficiency, and ultimately improve patient outcomes on a systemic level (Martin et al., 2022; Everson et al., 2024; Dixon et al., 2020; Ongkeko, 2024).

2. METHODOLOGY

A systematic review approach was employed following the PRISMA 2020 guidelines to ensure transparency and rigor. The review focused on literature published in 2024 to capture the most current research related to the topic. Multiple academic databases were searched, including PubMed, Scopus, and Web of Science, using a combination of relevant keywords and Boolean operators. These keywords were selected based on preliminary reviews and expert consultation to ensure comprehensive coverage of the subject matter.

All retrieved records were exported to a reference manager, and duplicates were identified and removed. Titles and abstracts of the remaining studies were screened independently by two reviewers to assess relevance to the research objectives. Any disagreements between the reviewers were resolved through discussion or by consulting a third reviewer.

After the initial screening, full texts of potentially eligible articles were retrieved and assessed against predefined inclusion and exclusion criteria. Studies were included if they presented original data, were peer-reviewed, and addressed key aspects of the research topic. Articles not published in English, non-peer-reviewed papers, and those lacking empirical data were excluded.

A total of 2,345 records were identified through database searches. After removing 1,077 duplicates, 1,268 records remained for title and abstract screening. Of these, 1,033 were excluded for not meeting the eligibility criteria. The full texts of 235 articles were assessed, and 197 were excluded based on detailed eligibility assessment, resulting in 38 studies being included in the final synthesis.

All included studies were analyzed for their methodological quality and relevance. Data were extracted using a standardized form, and themes were synthesized narratively. This process enabled the identification of patterns, gaps, and key findings across the selected studies.

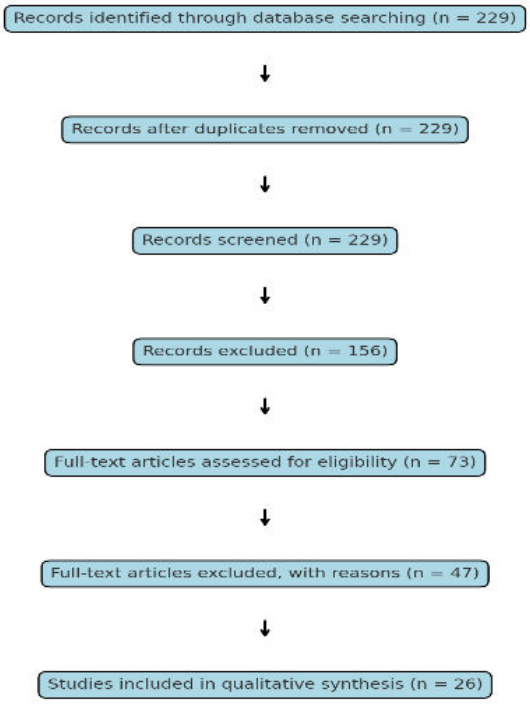

Figure 1. PRISMA Flowchart of the study methodology.

3. BACKGROUND AND EVOLUTION OF INTEROPERABILITY STANDARDS

The concept of health data interoperability has evolved alongside advancements in health information technology (health IT), driven by the growing complexity and fragmentation of healthcare delivery systems. The history of health data exchange standards reflects the ongoing effort to overcome these fragmentation issues and enable seamless communication across disparate healthcare systems (Ayo-Farai et al., 2024, Chintoh et al., 2024, Odionu et al., 2024). Initially, healthcare data exchange was limited to manual processes and paper-based records, which constrained the ability of providers to coordinate care or share critical information.

The transition to electronic health records (EHRs) and digital systems during the late 20th century brought the promise of more efficient healthcare delivery but also introduced new challenges related to data incompatibility, siloed systems, and varied data representations (Adepoju et al., 2024, Balogun et al., 2024, Okon, Zouo & Sobowale, 2024).

To address these challenges, early efforts in the 1980s and 1990s led to the creation of foundational data exchange protocols. Among the most influential initiatives was the development of Health Level Seven (HL7) by the HL7 organization in 1987. HL7 was designed to create a set of international standards for the transfer of clinical and administrative data between software applications used by various healthcare providers (Adhikari et al., 2024, Chukwurah et al., 2024, Zouo & Olamijuwon, 2024). HL7's Version 2 (V2) became one of the most widely implemented healthcare messaging standards in the world, particularly in hospitals and laboratories. It allowed for data sharing across systems, such as laboratory information systems and hospital information systems, by standardizing the format and content of messages. However, HL7 V2 lacked strict data definitions and relied heavily on customization, which led to variations in implementation and limited true interoperability.

The limitations of HL7 V2 highlighted the need for greater standardization and interoperability across the entire healthcare ecosystem. This need became more pronounced in the early 2000s as governments and healthcare organizations around the world began to invest in national health IT initiatives aimed at improving patient outcomes, enhancing data accessibility, and reducing costs. The U.S. The Health Information Technology for Economic and Clinical Health (HITECH) Act of 2009 was a major catalyst in this regard, as it promoted the adoption of EHR systems and provided incentives for meaningful use of health IT (Adewuyi et al., 2024, Edoh et al., 2024, Ogunboye et al., 2024). However, the widespread adoption of EHRs also revealed the inadequacies of existing data standards, particularly in enabling different systems to communicate effectively.

Recognizing the need for a more robust and flexible standard, HL7 International initiated the development of HL7 Version 3 (V3), which aimed to improve upon the weaknesses of V2 by using a more rigorous reference information model (RIM) and defined data types. Although HL7 V3 offered improved semantic interoperability, it was criticized for being overly complex and difficult to implement (Azubuike et al., 2024, Chigboh, Zouo & Olamijuwon, 2024). As a result, adoption of V3 was limited, and many health systems continued to rely on customized V2 implementations. The shortcomings of V2 and V3 demonstrated that the healthcare industry needed a new approach that combined ease of use, developer-friendliness, and robust data modeling. Figure 2 show Layered Fast Healthcare Interoperability Resources profile model presented by Rosenau et al., 2024.

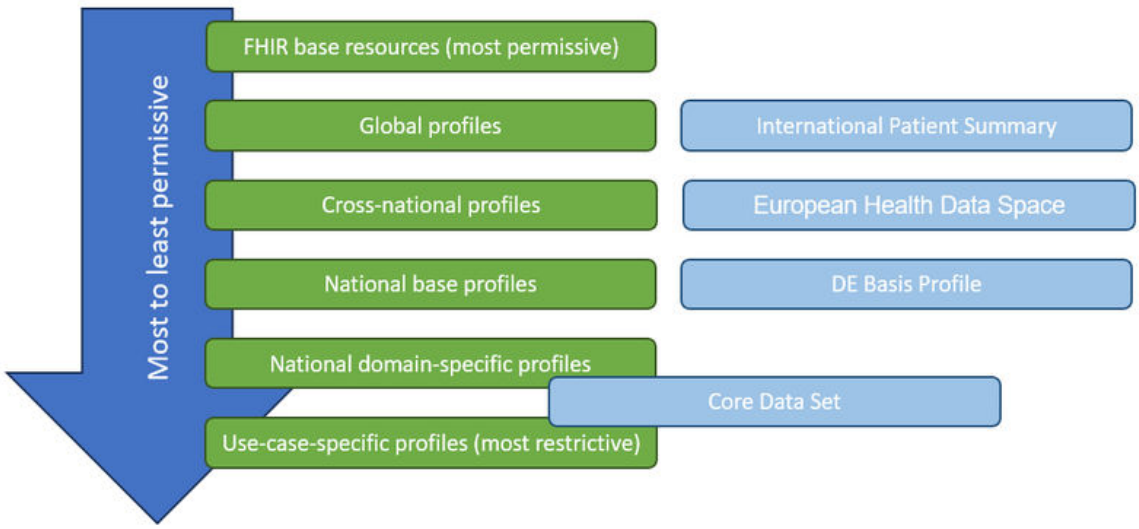

Figure 2. Layered Fast Healthcare Interoperability Resources profile model (Rosenau et al., 2024).

This realization led to the creation of Fast Healthcare Interoperability Resources (FHIR), which emerged as a modern and web-friendly standard for health data exchange. Officially introduced in 2014 by HL7 International, FHIR was developed to leverage the best features of HL7 V2 and V3 while addressing their limitations. Unlike its predecessors, FHIR was built on contemporary web technologies, including RESTful APIs, JSON, XML, and OAuth 2.0, making it more accessible to developers and easier to integrate into modern digital health applications (Atandero et al., 2024, Chintoh et al., 2024, Ohalete et al., 2024). FHIR also adopted a modular approach, organizing health information into discrete "resources" such as Patient, Observation, Medication, and Encounter. These resources can be combined, extended, or queried to meet various use cases, from clinical care to public health reporting.

The modularity and flexibility of FHIR have made it a game-changer in the field of health data interoperability. It supports a wide range of data exchange scenarios, from mobile health applications and patient portals to population health analytics and decision support systems. Moreover, FHIR's design promotes interoperability at both the syntactic and semantic levels by providing well-defined data structures and promoting the use of standardized terminologies such as SNOMED CT, LOINC, and ICD (Jahun et al., 2021, Matthew et al., 2021). As a result, FHIR has gained rapid acceptance among healthcare organizations, technology vendors, and policymakers worldwide. High-profile initiatives such as the Argonaut Project in the United States have further accelerated FHIR adoption by developing implementation guides and reference applications to support real-world use cases.

The journey from early health IT systems to the adoption of FHIR highlights the critical importance of standardization in achieving health data interoperability. Standardization is essential not only for ensuring consistency in data exchange but also for enabling automation, reducing duplication of efforts, and enhancing the quality and safety of patient care. Without common data models, formats, and terminologies, healthcare providers face significant barriers in sharing patient information, leading to inefficiencies, increased costs, and compromised patient outcomes (Adepoju et al., 2024, Folorunso et al., 2024, Olamijuwon & Zouo, 2024).

The evolution of HL7 and FHIR also underscores the importance of adaptability in health IT standards. As the needs of healthcare systems change—driven by factors such as aging populations, chronic disease prevalence, pandemics, and technological innovations—interoperability standards must evolve to support new models of care and data use. For instance, the rise of telemedicine, wearable health devices, and remote monitoring has created new demands for data integration and real-time communication across platforms (Abieba, Alozie, & Ajayi, 2025, Chintoh et al., 2025, Oso et al., 2025). FHIR, with its support for mobile and web-based technologies, is well-positioned to meet these evolving needs. Levels of interoperability, as presented by Adebesin et al., 2013, is shown in figure 3.

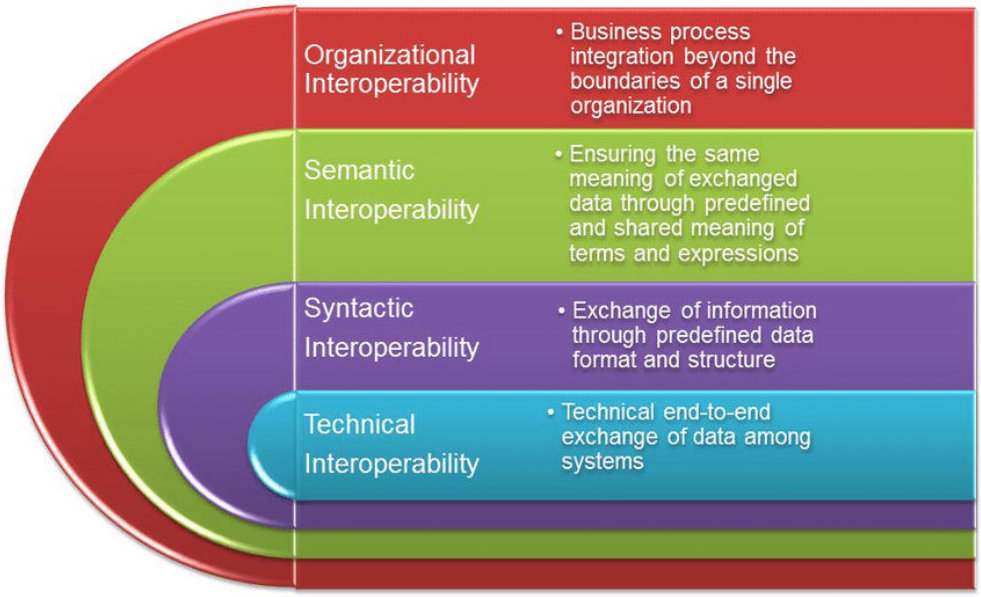

Figure 3. Levels of interoperability (Adebesin et al., 2013).

Beyond HL7 and FHIR, other interoperability standards have contributed to the broader ecosystem. The Clinical Document Architecture (CDA), developed under HL7 V3, provided a framework for the exchange of clinical documents, such as discharge summaries and progress notes. DICOM (Digital Imaging and Communications in Medicine) has been instrumental in standardizing the storage and transmission of medical imaging data. openEHR offers a different approach by focusing on the semantic modeling of clinical content and the long-term preservation of EHR data (Ayo-Farai et al., 2023, Babarinde et al., 2023). Each of these standards has played a role in shaping the interoperability landscape, and future progress will depend on how these standards can be harmonized and integrated to support comprehensive, cross-domain data exchange.

In summary, the background and evolution of health data interoperability standards reveal a dynamic and iterative process shaped by technological advancements, policy drivers, and the complex needs of healthcare stakeholders. From the early messaging frameworks of HL7 V2 to the modern, API-driven architecture of FHIR, the development of these standards has aimed to overcome fragmentation and enable meaningful data exchange (Adhikari et al., 2024, Edoh et al., 2024, Odionu et al., 2024). While significant progress has been made, the ongoing challenge is to ensure that interoperability standards are not only technically sound but also practically implementable, scalable, and aligned with the broader goals of improving health outcomes and system efficiency. As the healthcare industry continues to evolve, the role of interoperability standards will remain central to realizing the vision of connected, patient-centric, and data-driven care.

4. OVERVIEW OF MAJOR INTEROPERABILITY STANDARDS

Health data interoperability relies on a range of technical standards designed to enable seamless communication, data sharing, and integration among diverse health information systems. Over time, several interoperability standards have been developed, each with its own architecture, strengths, limitations, and areas of application.

Understanding these standards—particularly HL7 (Versions 2 and 3), FHIR, and others such as DICOM, IHE, openEHR, and XDS—is essential for appreciating how modern health systems strive to achieve effective and scalable interoperability (Ariyibi et al., 2024, Chintoh et al., 2024, Olorunsogo et al., 2024).

Health Level Seven (HL7) is one of the earliest and most widely implemented standards for health data exchange. HL7 Version 2 (v2), introduced in the late 1980s, was developed to standardize the communication of clinical and administrative data between hospital systems, such as laboratory information systems, radiology systems, and hospital information systems. The architecture of HL7 v2 is message-based and follows an event-driven approach, where different clinical events (e.g., Patient admission, discharge, or lab order) trigger the exchange of structured messages between systems (Adepoju et al., 2022, Ogbeta, Mbata & Udemezue, 2022). These messages are defined by specific segments and fields that follow a delimited format, typically using the pipe "|" symbol to separate elements. Jaleel et al., 2020, proposed in Figure 4, framework for Medical Data Interoperability through the collaboration of Healthcare Devices.

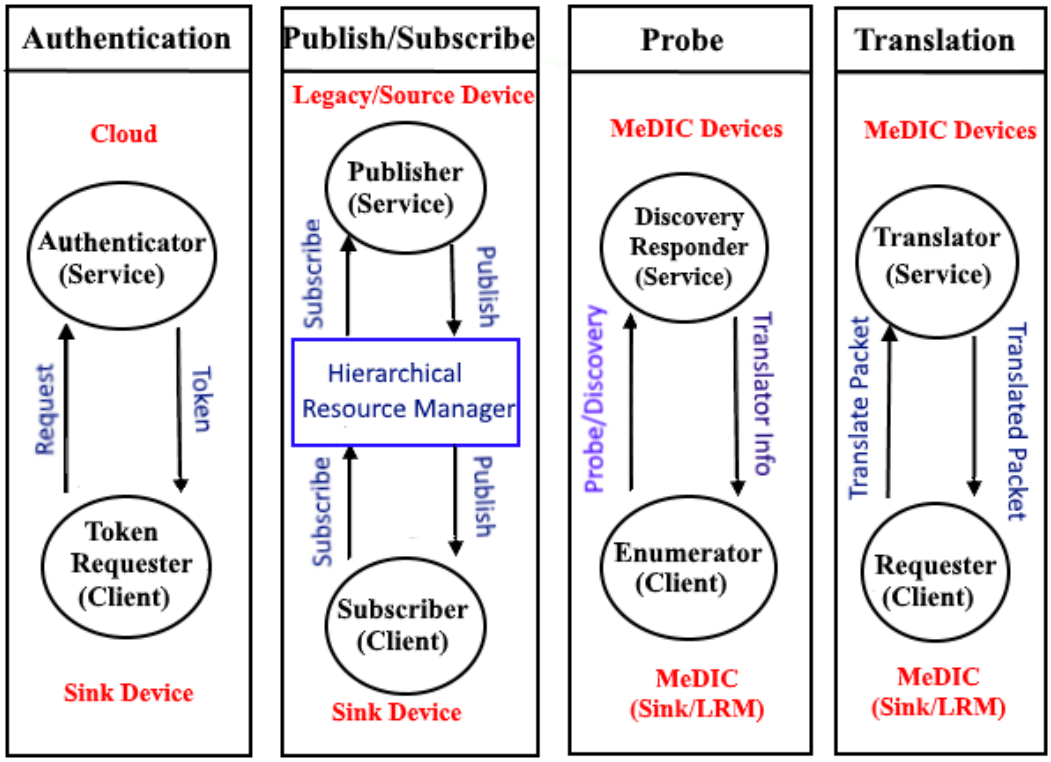

Figure 4. The proposed framework for Medical Data Interoperability through the Collaboration of Healthcare Devices (MeDIC) (Jaleel, et al., 2020).

One of the key strengths of HL7 v2 is its simplicity and flexibility. It allows institutions to implement only the messages they need and supports customization, which has facilitated widespread adoption. HL7 v2 is still operational in many healthcare settings globally due to its lightweight structure and long-standing industry support (Oladosu et al., 2021). However, this flexibility is also its major limitation. The lack of strict enforcement on implementation has led to significant variations across systems, undermining true interoperability (Adigun et al., 2024, Hussain et al., 2024, Ohalete et al., 2024). Because implementations are often customized, different systems may interpret or encode data differently, resulting in challenges with semantic consistency and data reuse.

In response to the inconsistencies of HL7 v2, HL7 International introduced HL7 Version 3 (v3) in the early 2000s. HL7 v3 aimed to improve semantic interoperability by introducing a more rigid and formal methodology based on the Reference Information Model (RIM). The RIM provided a consistent logical framework and vocabulary for representing health data, supporting clearer definitions and relationships among data elements. HL7 v3 also emphasized the use of XML for message encoding and attempted to create a more universally applicable set of standards (Adelodun & Anyanwu, 2024, Folorunso et al., 2024, Oshodi et al., 2024).

Despite these improvements, HL7 v3 struggled with practical adoption. Its architecture was considered complex and resource-intensive, both in terms of implementation and maintenance. The RIM-based approach, while conceptually robust, required steep learning curves and extensive training for developers. Furthermore, many vendors and health systems found it difficult to adapt their existing infrastructures to the rigid specifications of v3 (Ayo-Farai et al.. 2024, Ike et al., 2024, Olorunsogo et al., 2024). As a result, HL7 v3 failed to achieve the widespread success of its predecessor, and its adoption remained limited primarily to specific regions or specialized projects.

Recognizing the need for a more practical and modern solution, HL7 International began developing Fast Healthcare Interoperability Resources (FHIR) around 2011, with official releases starting in 2014. FHIR was designed to combine the best features of HL7 v2 and v3 with contemporary web development technologies, making it easier to implement, use, and scale. FHIR is based on RESTful API principles, which are widely used in modern software development. It also supports data formats such as JSON and XML, which are more familiar and accessible to developers across industries (Afolabi, Chukwurah, & Abieba, 2025, Chintoh et al., 2025, Oso et al., 2025).

At the heart of FHIR is its modular resource model. Instead of relying on large, monolithic messages, FHIR organizes health data into discrete, reusable components called “resources.” Each resource represents a specific entity—such as a Patient, Observation, Encounter, or Medication—and can be accessed, queried, or updated individually via HTTP methods (GET, POST, PUT, DELETE). These resources are designed to be extensible and can be combined or profiled to suit specific use cases, making FHIR highly adaptable to the diverse needs of healthcare systems (Adepoju et al., 2024, Chintoh et al., 2024, Sule et al., 2024).

The extensibility of FHIR is one of its major advantages. It enables implementers to define custom profiles and extensions while maintaining compatibility with the core standard. This ensures that local needs can be addressed without sacrificing interoperability with external systems. Moreover, FHIR’s emphasis on standard terminologies like SNOMED CT, LOINC, and ICD further promotes semantic consistency and data quality (Alli & Dada, 2023, Hussain et al., 2023).

Compared to earlier HL7 versions, FHIR represents a significant advancement. Its use of modern technologies, support for lightweight integration, and modularity make it suitable for a wide range of applications—from mobile apps and patient portals to population health management and research analytics. Importantly, FHIR aligns with the growing trend of patient-centric and data-driven healthcare, supporting real-time access, usability, and innovation (Adekola et al., 2023, Ikwuanusi, Adepoju & Odionu, 2023).

Beyond HL7 and FHIR, several other standards and frameworks play vital roles in achieving comprehensive health data interoperability. The Digital Imaging and Communications in Medicine (DICOM) standard is one of the most important in the field of medical imaging. Developed by the National Electrical Manufacturers Association (NEMA), DICOM standardizes the format and exchange of medical images such as X-rays, MRIs, and CT scans (Atta et al., 2021, Dirlikov, 2021). It ensures that imaging devices and systems from different vendors can store, retrieve, and display images consistently and is widely implemented in radiology and diagnostic imaging departments.

Another important initiative is Integrating the Healthcare Enterprise (IHE), which focuses on promoting the coordinated use of established standards to address specific clinical needs. Rather than developing new standards, IHE creates integration profiles that specify how existing standards like HL7, DICOM, and others should be used together to achieve interoperability for particular workflows, such as laboratory reporting or patient identification. IHE has been instrumental in encouraging conformance testing and harmonization across vendors and systems (Ayo-Farai et al.. 2023, Babarinde et al., 2023).

openEHR is another interoperability framework that approaches the problem from a clinical modeling perspective. It provides a platform-independent standard for storing and managing EHR data using archetypes—reusable, domain-specific data models that represent clinical concepts. openEHR separates data from applications, enabling long-term preservation of health records and facilitating reuse across different systems and contexts (Adepoju et al., 2022, Opia, Matthew & Matthew, 2022). While not as widely adopted as HL7 or FHIR, openEHR is recognized for its rigorous modeling methodology and has been used in national health systems such as those in Norway and Brazil.

SMART on FHIR (Substitutable Medical Applications, Reusable Technologies) is a framework built on top of FHIR that focuses on enabling the development of interoperable healthcare apps. It provides a standardized way for third-party applications to connect securely to EHR systems using FHIR APIs and OAuth 2.0 for authentication. SMART on FHIR supports plug-and-play app development, allowing tools for decision support, patient engagement, and data visualization to be seamlessly integrated into existing workflows (Jahun et al., 2021, Ogbeta, Mbata & Udemezue, 2021).

Cross-enterprise Document Sharing (XDS), developed under the IHE framework, is designed to support the sharing of clinical documents across healthcare enterprises. XDS defines an architecture for registering, locating, and accessing patient records stored in multiple document repositories, using a centralized registry and distributed repository model. It plays a critical role in enabling document-based interoperability, particularly in large-scale health information exchanges (Afolabi, Chukwurah & Abieba, 2025, Edwards et al., 2025).

Together, these standards and frameworks represent the core of modern health data interoperability. Each addresses different layers and domains within the healthcare ecosystem—ranging from messaging and APIs to imaging, clinical modeling, and document exchange. As the healthcare industry continues to evolve, the integration, harmonization, and adoption of these standards will be crucial in enabling more connected, efficient, and patient-centered care (Azubuike et al., 2024, Chintoh et al., 2024, Odionu et al., 2024). Understanding the strengths, limitations, and appropriate use cases of each is essential for designing systems that can meet the growing demand for secure, scalable, and meaningful health data exchange.

5. COMPARATIVE ANALYSIS

A comprehensive comparative analysis of health data interoperability standards such as FHIR, HL7 (Versions 2 and 3), and other related frameworks highlights critical differences in their structure, usability, adaptability, and overall impact on healthcare integration. Each standard was developed in response to specific technological and clinical needs of its time, and while they all aim to facilitate the seamless exchange of healthcare data, they do so through fundamentally different architectural approaches, implementation strategies, and support mechanisms (Adelodun & Anyanwu, 2025, Ibeh et al., 2025, Oso et al., 2025).

One of the most prominent distinctions among these standards lies in their structural design and compatibility. HL7 Version 2 (v2), being one of the earliest health data exchange standards, follows a message-based architecture that uses delimited text formats to transmit information between systems. It operates using event-driven messages, where each message corresponds to a clinical or administrative event, such as patient admission, lab order, or discharge (Adepoju et al., 2023, Balogun et al., 2023). Although HL7 v2 is relatively straightforward, its structure allows for significant customization, which has led to a high degree of variability across implementations. This variability limits interoperability across organizations, as two institutions may use the same HL7 v2 message type but interpret or format it differently.

HL7 Version 3 (v3) attempted to address this issue by introducing a more rigorous structure based on the Reference Information Model (RIM). The intent was to provide a consistent data model across all message types to reduce variation and improve semantic interoperability. However, v3's complexity and rigid structure made it difficult to implement, and its reliance on XML formatting contributed to verbosity and performance overhead. Compatibility with existing HL7 v2 implementations was also limited, requiring costly adaptations or dual-system maintenance (Adelodun & Anyanwu, 2024, Kelvin-Agwu et al., 2024, Olorunsogo et al., 2024).

FHIR, by contrast, represents a paradigm shift in structural design. It uses a modular architecture centered around "resources," which are discrete units of health data (e.g., Patient, Observation, Medication). These resources are designed to be accessed individually and combined as needed. FHIR supports modern data formats such as JSON and XML and is built on RESTful web principles, making it highly compatible with current web technologies and services (Alli & Dada, 2022, Ige et al., 2022). The modularity and resource-based structure of FHIR promote better alignment with contemporary software engineering practices and support smoother data exchange with greater semantic clarity and consistency. Its compatibility with web standards and ability to support various transport protocols give it an edge in flexibility and integration with broader health IT ecosystems.

When evaluating ease of implementation and developer support, FHIR stands out as the most accessible and developer-friendly standard. Its use of RESTful APIs mirrors common patterns in mainstream software development, significantly lowering the barrier to entry for new developers. Extensive documentation, open-source reference implementations, testing tools, and a growing developer community further support its adoption (Austin-Gabriel et al., 2021, Dirlikovet al., 2021). FHIR's accessibility has also led to the emergence of plug-and-play applications, facilitated by frameworks such as SMART on FHIR, which allow third-party apps to connect securely to health data using standard protocols.

These innovations make FHIR attractive not only to large healthcare institutions but also to startups, academic researchers, and public health agencies.

In contrast, HL7 v2 and v3 require more specialized knowledge and experience, particularly in parsing messages, handling encoding rules, and customizing segments. HL7 v3, with its steep learning curve and complex modeling via the RIM, has seen limited traction in developer communities. Furthermore, the lack of consistency in HL7 v2 implementations often forces developers to write custom logic for different health systems, increasing development time and costs. These challenges make HL7-based systems less appealing for new health IT projects that prioritize agility and rapid deployment (Ayo-Farai et al., 2023, Ikwuanusi, Adepoju & Odionu, 2023).

Flexibility, scalability, and extensibility are also key factors that differentiate these standards. HL7 v2, while widely used, is limited in its ability to scale across diverse care settings due to its loose structure and need for extensive customization. HL7 v3 attempted to resolve these issues but fell short due to its complexity and poor adaptability to evolving technologies. FHIR, on the other hand, was explicitly designed with flexibility and scalability in mind (Adepoju et al., 2023, Ike et al., 2023). Its modular resource model allows implementers to adopt only the parts they need, while its support for extensions ensures that local requirements can be accommodated without breaking standard compatibility.

FHIR's scalability is further enhanced by its stateless design and efficient data querying capabilities. Its use of RESTful architecture enables lightweight interactions suitable for mobile devices, cloud platforms, and IoT systems. This positions FHIR as a future-ready standard capable of supporting population-level analytics, remote monitoring, and telehealth applications. Its adaptability also makes it suitable for various deployment models, including cloud-native solutions and hybrid on-premise architectures (Adaramola, et al., 2024, Kelvin-Agwu, et al., 2024, Temedie-Asogwa, et al., 2024).

Performance in real-world clinical settings depends on several factors, including response times, reliability, and ease of integration into existing workflows. HL7 v2, due to its simplicity and long-standing presence in hospitals, performs reliably in environments where it is well-configured and standardized. It is particularly effective in high-throughput environments such as labs and pharmacies, where predefined event messages can be transmitted quickly and efficiently. However, the customization required to align with different vendor systems remains a challenge for cross-institutional interoperability (Afolabi, Chukwurah, & Abieba, 2025, Odionu et al., 2025).

HL7 v3 has seen limited use in clinical settings due to its complexity, and most implementations are in niche or research-focused domains. Its performance is hindered by verbose messages and the overhead of the RIM-based modeling, making it less suited for real-time clinical interactions or lightweight applications.

FHIR has shown promising performance in clinical settings where modern infrastructure supports web-based services. It excels in environments that require real-time access to patient data, especially where mobile devices or decision-support tools are involved. Studies and pilot implementations in the United States and Europe have shown that FHIR-based systems improve access to up-to-date clinical information, streamline workflows, and support patient engagement through apps and portals (Ayanbode et al., 2024, Majebi, Adelodun, & Anyanwu, 2024, Zouo & Olamijuwon, 2024).

However, FHIR's performance can be influenced by server load, query complexity, and the availability of robust FHIR implementations on vendor platforms.

Integration with legacy systems remains one of the most important considerations in the healthcare industry, where many organizations still rely on older, monolithic EHR systems and infrastructure. HL7 v2 enjoys the highest compatibility with legacy systems, as it was widely adopted during the early phases of digital health transformation. Most legacy EHRs and lab systems have built-in support for HL7 v2 messages, and many health information exchanges are based on v2 protocols (Ayo-Farai et al., 2024, Oddie-Okeke et al., 2024, Uwumiro et al., 2024).

HL7 v3, by contrast, has poor integration with legacy systems due to its different modeling approach and data representation. Its lack of widespread adoption also means that there is less tooling and fewer integration pathways available for legacy environments.

FHIR's ability to integrate with legacy systems depends largely on the existence of middleware or adapter solutions that translate legacy data formats into FHIR resources. While this adds an initial layer of complexity, many health IT vendors have begun to offer FHIR interfaces that sit on top of legacy databases, exposing standardized APIs while maintaining the underlying system architecture. In this way, FHIR enables a gradual transition from legacy systems to modern interoperability without requiring full system overhauls (Adepoju et al., 2023, Balogun et al., 2023.

In conclusion, this comparative analysis reveals that while HL7 v2 laid the groundwork for electronic data exchange in healthcare and continues to serve as a backbone for many institutions, its limitations in standardization and flexibility hinder its utility in modern health IT environments. HL7 v3, though conceptually more robust, proved too complex for widespread implementation. FHIR emerges as the most promising standard, offering a balance of structure, developer accessibility, and extensibility (Ayo-Farai et al., 2024, Odionu et al., 2024, Olowe et al., 2024). Its alignment with modern technologies, strong community support, and adaptability to evolving healthcare needs position it as the leading choice for future interoperability efforts. However, the coexistence of multiple standards requires a strategic and integrated approach to ensure that health systems can transition smoothly, maximize interoperability, and ultimately improve patient care and health outcomes (Adelodun & Anyanwu, 2024, Kelvin-Agwu et al., 2024).

6. SEMANTIC INTEROPERABILITY AND DATA GOVERNANCE

Semantic interoperability and data governance are central to realizing the full potential of health data exchange. While structural and syntactic interoperability enable systems to transmit and interpret the format of data, semantic interoperability ensures that the meaning of exchanged information is accurately understood by all systems and users involved.Without semantic consistency, the data may be technically shareable but clinically unusable, potentially leading to misinterpretations, patient safety risks, and operational inefficiencies (Alli & Dada, 2024, Fasipe & Ogunboye, 2024, Ogundairo et al., 2024). In the context of health data standards such as FHIR, HL7, and others, semantic interoperability is achieved through the adoption of common data models and standardized medical terminologies, as well as robust data governance practices that safeguard integrity, accountability, and patient autonomy (Ayinde et al., 2021, Hussain et al., 2021).

The use of standardized terminologies such as SNOMED CT (Systematized Nomenclature of Medicine Clinical Terms), LOINC (Logical Observation Identifiers Names and Codes), and ICD (International Classification of Diseases) plays a crucial role in enabling semantic interoperability (Adepoju et al., 2023, Ezeamii et al., 2023). These coding systems provide consistent, machine-readable representations of clinical concepts across languages, settings, and care environments. For example, SNOMED CT supports comprehensive representation of diagnoses, findings, procedures, and other clinical terms, while LOINC is widely used for lab tests and clinical observations. When integrated into health data standards like FHIR or HL7 v3, these terminologies ensure that a diagnosis or lab result means the same thing across different systems, regardless of vendor-specific implementations or regional differences (Adegoke et al., 2022, Patel, et al., 2022).

FHIR, in particular, has made strong provisions for incorporating these standard terminologies into its resource model. Fields within FHIR resources are often bound to value sets that reference SNOMED CT, LOINC, or other recognized code systems. For instance, a FHIR Observation resource used to report a lab result would reference LOINC for test identification and SNOMED CT for clinical interpretation (Afolabi et al., 2023, Ikwuanusi, Adepoju & Odionu, 2023). This alignment not only promotes data consistency but also enhances the potential for advanced data analytics, clinical decision support, and population health management by ensuring that data retains its intended meaning as it moves across systems and contexts.

Despite the existence of these terminologies and standards, achieving semantic consistency in real-world implementations remains challenging. One key issue is the variability in how different organizations adopt and use standardized codes. Many healthcare providers still rely on local or proprietary code systems, and even when standard codes are used, they may not be applied uniformly (Adepoju et al., 2023, Nnagha, et al.,2023). A lab test for glucose might be labeled differently or coded under a different identifier across institutions, even if it refers to the same clinical concept. Mapping these variations to standard codes is a complex and error-prone process, requiring both automated tools and human oversight.

In addition to inconsistent code usage, semantic interoperability is hindered by differences in data modeling practices. For example, different systems may model the same clinical event—such as a medication prescription or an allergy—using different structures or data fields. HL7 v2, due to its flexibility, often leads to divergent implementations that are technically syntactic but semantically incompatible (Ajayi et al., 2024, Ezeamii et al., 2024, Ohalete et al., 2024). HL7 v3 attempted to address this with its Reference Information Model (RIM), but its complexity and rigidity limited adoption. FHIR's modular resource approach and support for profiling and extensions offer a more balanced path, but they still require careful governance to prevent fragmentation and misalignment.

A critical component of semantic interoperability is data governance, which includes data provenance, consent management, and patient control over their health information. Data provenance refers to the documentation of the origin, history, and lifecycle of a data element. Knowing where a piece of data came from, who created it, and under what context is essential for ensuring trust, reliability, and appropriate use (Adelodun & Anyanwu, 2024, Kelvin-Agwu, et al., 2024, Zouo & Olamijuwon, 2024). Provenance information also plays a crucial role in legal and ethical accountability, especially in environments involving data aggregation, clinical trials, or cross-border information exchange.

FHIR has built-in support for tracking data provenance through its Provenance resource, which records metadata such as the author, timestamp, source system, and purpose of creation or modification. This allows systems to trace the history of any data element, which is particularly valuable in federated or multi-institutional environments where data may pass through various intermediaries (Adepoju et al., 2023, Nwaonumah et al., 2023). Provenance tracking is also important for auditing and maintaining data integrity, especially when multiple users contribute to a patient's record or when data is used for secondary purposes such as research or public health reporting.

Closely tied to data governance is the management of patient consent and control over health data. Modern healthcare emphasizes patient centricity and shared decision-making, which includes respecting patient preferences about how their data is accessed, shared, and used. Effective consent management ensures that patients are informed about the uses of their data and that their permissions are respected across systems (Adelodun & Anyanwu, 2025, Ige et al., 2025). This is particularly important in cases involving sensitive health information, such as mental health records, genetic data, or substance use treatment histories.

FHIR supports consent representation through the Consent resource, which allows health IT systems to record, manage, and enforce patient preferences for data sharing. This resource can encode whether a patient has agreed to share certain types of information, under what conditions, and with whom. Combined with access control mechanisms and provenance tracking, consent management tools can help ensure that data is used ethically and in accordance with patients' wishes (Alli & Dada, 2023, Majebi et al., 2023).

Compliance with data privacy laws such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States and the General Data Protection Regulation (GDPR) in the European Union further elevates the importance of robust data governance frameworks. HIPAA mandates safeguards for the protection of personal health information, including rules around access, disclosure, and breach notification (Adepoju et al., 2023, Ogbeta et al., 2023). Similarly, GDPR imposes strict requirements on data controllers and processors, including principles of data minimization, purpose limitation, and the right to be forgotten.

Interoperability standards must support these legal requirements not only at the policy level but through technical implementation. This includes secure data transmission protocols (e.g., TLS), authentication and authorization mechanisms (e.g., OAuth 2.0), encryption of data at rest and in transit, and audit logging of data access. FHIR has incorporated these considerations into its security implementation guides, offering recommended practices for building HIPAA- and GDPR-compliant systems (Adekola et al., 2023, Ezeamii et al., 2023).

One of the unique challenges posed by GDPR is the emphasis on patient rights, such as the right to access, rectify, and delete their data. Systems built on older standards like HL7 v2 or v3 may lack the granularity and infrastructure to efficiently support these operations, especially in centralized architectures. FHIR, with its resource-centric and RESTful architecture, provides a more natural and efficient pathway to implementing these rights, enabling fine-grained control over data elements and supporting dynamic queries and updates (Ajayi et al., 2025, Ogbeta, Mbata & Udemezue, 2025).

The integration of semantic interoperability and data governance is critical for the future of digital health. It not only supports accurate and meaningful data exchange but also ensures that data is managed responsibly, securely, and in alignment with ethical and legal frameworks.

As health systems evolve toward more distributed, patient-centered, and data-driven models of care, the demand for robust semantic standards and governance tools will continue to grow. Health data interoperability is no longer just a technical challenge; it is a matter of public trust, legal compliance, and clinical safety (Adepoju et al., 2024, Kelvin-Agwu et al., 2024, Shittu et al., 2024). Ensuring that systems can exchange data with shared understanding, respect for patient rights, and secure handling of sensitive information is fundamental to achieving high-quality, equitable, and sustainable healthcare.

7. CHALLENGES AND LIMITATIONS

Despite the considerable progress made in developing and implementing health data interoperability standards such as FHIR, HL7, and others, significant challenges and limitations persist. These issues continue to hinder the seamless exchange of health information across different systems, institutions, and geographic regions. A critical review of these standards reveals several persistent barriers that must be addressed to fully realize the vision of integrated, patient-centered healthcare (Adelodun & Anyanwu, 2024, Majebi, Adelodun & Anyanwu, 2024). Key among these are vendor lock-in, fragmentation in standard adoption, inconsistent data formatting and quality, and the complexities of cross-border data exchange.

One of the most pressing challenges in achieving effective interoperability is vendor lock-in and the prevalence of proprietary implementations. Many health information system vendors have developed their platforms in ways that do not fully align with interoperability standards or allow limited access to data unless clients use proprietary tools or interfaces (Alli & Dada, 2023, Fagbule et al., 2023). While vendors may offer HL7 or FHIR-compatible APIs, these are often implemented in ways that only partially conform to the standard, adding proprietary extensions or custom logic that make it difficult for external systems to interact without detailed knowledge of the specific implementation. As a result, healthcare organizations can find themselves reliant on a single vendor's ecosystem, facing high costs and technical barriers when attempting to switch systems or integrate third-party solutions (Adepoju et al., 2024, Ezeamii et al., 2024, Okhawere et al., 2024)

This issue is further compounded by the competitive nature of the healthcare IT market, where vendors may be reluctant to open their systems fully, fearing loss of market share or reduced service revenues. Even when standards like FHIR are supported, access to full functionality often requires purchasing additional modules or services. Such practices restrict innovation and hinder collaboration across the healthcare continuum. True interoperability should enable health data to flow seamlessly between systems, regardless of vendor, but proprietary limitations continue to restrict this possibility in practice (Adelodun et al., 2018, Ike et al., 2021).

Fragmentation in the adoption of interoperability standards across institutions is another significant limitation. While many large hospitals and health systems in high-income countries have adopted standards such as HL7 v2 or FHIR, smaller clinics, rural hospitals, and healthcare facilities in low- and middle-income countries may still rely on outdated systems or paper-based records (Ajayi, Alozie, & Abieba, 2025, Ekeh et al., 2025). This uneven adoption creates gaps in data flow and complicates efforts to build comprehensive health information networks. Even within a single healthcare system, different departments or subsidiaries may use different versions of the same standard or entirely different standards, leading to internal silos and redundant processes.

The transition from older standards like HL7 v2 to more modern ones like FHIR is not always smooth. Institutions may implement hybrid systems where some components use v2 messages while others adopt FHIR resources, resulting in interoperability "patches" that are complex to maintain and prone to failure. Moreover, even when a standard is adopted, the degree to which it is implemented can vary widely (Adepoju et al., 2024, Majebi, Adelodun, & Anyanwu, 2024). One hospital might use a minimal FHIR implementation for a patient portal, while another may have built a fully integrated system for data exchange across multiple departments. Without consistent and comprehensive adoption, the benefits of interoperability remain limited and fragmented.

In addition to fragmentation, inconsistent data formatting and quality present a major challenge to interoperability. Health data often originates from a wide variety of sources, including EHRs, laboratory systems, radiology systems, wearable devices, and mobile health apps. Each source may use different data entry conventions, terminologies, and coding systems. For example, one system may use SNOMED CT to code clinical conditions, while another uses ICD-10 (Adelodun & Anyanwu, 2024, Obianyo et al., 2024, Olowe et al., 2024). Similarly, units of measurement, date formats, and even spelling conventions may vary, making it difficult to harmonize and accurately interpret data when it is exchanged across systems.

These inconsistencies can undermine clinical decision-making and data analytics efforts. If lab results are reported with different units or missing context, clinicians may draw incorrect conclusions. In the context of population health, inconsistent data formatting can skew analytics and policy recommendations. Data quality issues such as incomplete records, duplicate entries, outdated information, and transcription errors further exacerbate the problem. Effective data exchange is not only about the ability to transfer data but also about ensuring that the data is accurate, meaningful, and actionable when received (Anyanwu et al., 2024, Matthew et al., 2024, Okoro et al., 2024).

FHIR was designed in part to address data formatting inconsistencies by providing clearly defined resource structures and encouraging the use of standard terminologies. However, its flexibility can also be a double-edged sword. While FHIR allows for custom extensions to accommodate local needs, overuse of these extensions can lead to interoperability problems when different systems define and implement them in divergent ways. The lack of strict enforcement of implementation guidelines results in variations that require additional effort to reconcile, validate, and integrate (Alozie et al., 2024, Ezeamii et al., 2024, Okobi et al., 2024).

Barriers to cross-border data exchange represent another formidable challenge, especially as healthcare becomes increasingly globalized. Patients today often receive care in multiple countries, whether due to migration, medical tourism, or international travel.

Public health initiatives, research collaborations, and pandemic responses also require the ability to share health data across national borders. However, legal, technical, and cultural differences create significant obstacles to this form of interoperability (Adepoju et al., 2024, Kelvin-Agwu et al., 2024, Oladosu et al., 2024).One of the main barriers is the divergence in data privacy regulations across jurisdictions. While standards like HIPAA in the United States and GDPR in the European Union aim to protect personal health information, their requirements differ significantly in terms of consent, data access rights, and data transfer provisions.

For instance, GDPR imposes strict conditions on the cross-border transfer of personal data outside the European Economic Area, requiring that recipient countries offer an "adequate" level of data protection (Ogundairo et al., 2023, Uwumiro et al., 2023). These legal constraints complicate the sharing of patient records with healthcare providers or researchers in other regions.

Beyond legal differences, technical disparities such as incompatible systems, differing national standards, and language barriers further impede cross-border interoperability. Some countries have developed their own national health IT frameworks and terminologies, which may not align neatly with international standards. Translating not only language but clinical context and medical practices can be complex, especially when dealing with free-text fields or culturally specific health concepts (Akinade et al., 2022, Patel et al., 2022). Furthermore, resource constraints in low- and middle-income countries may limit the ability to adopt and maintain interoperable systems at all.

Efforts to create international interoperability frameworks, such as the Global Digital Health Partnership (GDHP) and initiatives by the World Health Organization (WHO), aim to promote harmonization and shared best practices. However, the pace of progress is uneven, and true cross-border interoperability remains an aspirational goal rather than a widespread reality. More coordinated international efforts are needed to develop common frameworks, legal agreements, and infrastructure that support the secure and ethical sharing of health data across borders (Akinade et al., 2021, Bidemi et al., 2021).

In summary, despite the evolution and growing adoption of interoperability standards like HL7 and FHIR, substantial challenges continue to hinder seamless data exchange in healthcare. Vendor lock-in and proprietary systems restrict open access and innovation, while fragmented adoption across institutions leads to data silos and inefficiencies. Inconsistent data formatting and quality further complicate integration and clinical decision-making (Adepoju et al., 2025, Amafah et al., 2025, Ige et al., 2025), and cross-border data exchange remains stifled by legal, technical, and organizational barriers. Addressing these limitations requires a multi-faceted approach, involving not just technological innovation but also policy reform, stakeholder collaboration, and a commitment to open, patient-centered data governance. Only through such coordinated efforts can health systems achieve the full promise of interoperability and deliver safer, more efficient, and equitable care for all.

8. FUTURE DIRECTIONS AND RECOMMENDATIONS

As the demand for seamless health data exchange continues to grow, the future of health data interoperability depends on the strategic evolution of standards, supportive policies, and multi-stakeholder collaboration. The path forward requires addressing current limitations in interoperability frameworks like FHIR and HL7 while proactively shaping an ecosystem that is secure, adaptable, and patient-centric (Ajayi, Alozie & Abieba, 2025, Ekeh et al., 2025). Future directions and recommendations must focus on harmonizing standards, aligning policies, promoting open APIs and rigorous interoperability testing, fostering collaboration, and integrating emerging technologies such as artificial intelligence (AI) and blockchain to enable more robust, scalable, and intelligent data exchange mechanisms.

One of the most pressing future directions is the harmonization of existing interoperability standards and alignment of policy frameworks.

As it stands, healthcare organizations often grapple with a landscape cluttered with competing or overlapping standards, including HL7 v2, HL7 v3, FHIR, CDA, DICOM, and openEHR. While each serves specific use cases, the lack of coordination between them creates fragmentation and complexity (Anyanwu et al., 2024, Majebi, Adelodun, & Anyanwu, 2024). Moving forward, there must be a concerted global effort to map, consolidate, and harmonize these standards into a more cohesive framework that can support varied clinical, administrative, and research needs. This does not necessarily imply the elimination of existing standards, but rather the creation of robust interoperability bridges, mapping tools, and unified implementation guides that help developers, healthcare providers, and policymakers navigate and integrate across these standards with minimal friction.

Policy alignment is equally important in driving effective and ethical interoperability. Regulatory environments often lag behind technological advancements, resulting in conflicting or unclear rules that deter cross-institutional and cross-border data sharing. Harmonizing data protection and privacy policies across jurisdictions can create a more stable foundation for interoperable systems. For example, reconciling differences between the Health Insurance Portability and Accountability Act (HIPAA) in the United States and the General Data Protection Regulation (GDPR) in Europe will be vital for facilitating global collaboration in public health, research, and clinical care (Adepoju et al., 2024, Kelvin-Agwu et al., 2024, Olowe, et al., 2024). Governments and international bodies should collaborate to establish interoperability-friendly regulatory frameworks that uphold data privacy while enabling innovation. These policies should also include mechanisms for accountability, enforcement, and standard conformance assessment.

Encouraging the use of open application programming interfaces (APIs) and implementing systematic interoperability testing are also key recommendations for future development. Open APIs are central to unlocking health data from proprietary systems and enabling third-party applications to contribute meaningfully to care delivery, analytics, and patient engagement. FHIR has made significant progress in this area by adopting web-based RESTful APIs and supporting common data formats like JSON and XML (Adelodun & Anyanwu, 2024, Ezeamii et al., 2024, Okoro et al., 2024). However, the mere existence of APIs is not sufficient; their openness, consistency, and adherence to standards must be ensured. Health IT vendors should be incentivized or required to publish well-documented, standard-compliant APIs and provide public access to test environments where developers can build and validate interoperable applications.

Interoperability testing should become a standard practice throughout the development and procurement cycles of health IT systems. Just as medical devices undergo certification, software applications should be subject to rigorous, independent testing to ensure they meet interoperability criteria and function seamlessly across environments (Al Zoubi et al., 2022). Certification programs—such as those developed by the Office of the National Coordinator for Health Information Technology (ONC) in the U.S. or Integrating the Healthcare Enterprise (IHE) profiles—should be expanded and adapted to evolving standards like FHIR. In addition, public-private partnerships can help fund and maintain testing infrastructure, including sandboxes, validation tools, and community-driven test beds.

A future-oriented strategy also calls for the strengthening of collaboration among all stakeholders involved in health data exchange. This includes not only healthcare providers and IT vendors but also patients, payers, researchers, public health agencies, and standards development organizations. Multi-stakeholder governance structures can ensure that interoperability initiatives reflect diverse needs, anticipate ethical concerns, and respond to emerging challenges (Matthew et al., 2021, Oladosu et al., 2021).

For example, involving patients in the governance of consent models and data-sharing policies ensures that systems respect individual rights and preferences. Cross-sector collaborations also help align incentives and accelerate innovation. When technology vendors, clinicians, and policymakers work together, they can co-develop practical solutions that are more likely to be adopted and sustained.

Furthermore, collaboration should extend beyond national borders to address the growing need for global health data exchange. International organizations such as the World Health Organization (WHO), the Global Digital Health Partnership (GDHP), and the International Medical Informatics Association (IMIA) can play a central role in setting global priorities, sharing best practices, and fostering consensus on standards and ethics (Akinade et al., 2025, Ekeh et al., 2025). Pilot projects involving multinational data sharing—such as collaborative pandemic surveillance, cross-border EHR integration, or international clinical trials—can serve as test cases for refining technical and governance models that support trustworthy and effective global interoperability.

The integration of emerging technologies such as artificial intelligence (AI) and blockchain represents a promising direction for enhancing interoperability in ways previously unattainable. AI, especially when combined with large-scale health data sets, can be leveraged to automate and improve semantic interoperability. Natural language processing (NLP) tools can convert unstructured clinical notes into standardized, codified data, thereby enriching EHRs and making them more interoperable (Ogunboye et al., 2023, Ogundairo et al., 2023). AI-powered algorithms can also assist in mapping non-standardized data to recognized terminologies such as SNOMED CT and LOINC, bridging gaps that manual processes struggle to overcome. Additionally, predictive analytics powered by AI can help identify high-risk patients across disparate systems, improving clinical decision support and care coordination.

Blockchain technology, though still in its early stages in healthcare, holds potential for addressing critical challenges around data integrity, provenance, and trust. A blockchain-enabled health data exchange system could create immutable records of data transactions, ensuring transparency and accountability in how data is accessed and used. Smart contracts on blockchain platforms could automate data-sharing agreements and consent management, enabling patients to control access to their health information dynamically (Adepoju, et al., 2022).While scalability and regulatory acceptance are current limitations of blockchain in healthcare, ongoing research and pilot initiatives are exploring ways to integrate it with interoperability frameworks like FHIR in a secure, efficient, and privacy-preserving manner.

To maximize the benefits of AI and blockchain, interoperability standards must evolve to accommodate these technologies. For instance, FHIR resources could be extended to include metadata fields that support AI-generated insights or blockchain transaction hashes. Standards organizations should also work closely with technology developers to ensure that emerging tools and platforms align with established data exchange models and privacy frameworks (Adelodun & Anyanwu, 2025, Ogbeta, Mbata & Udemezue, 2025).

In conclusion, the future of health data interoperability depends on a multifaceted strategy that embraces both technological innovation and collaborative governance. Harmonizing existing standards and aligning global policies will provide a more coherent foundation for interoperability. Encouraging the adoption of open APIs and rigorous testing will ensure technical compatibility and system reliability (Al Hasan, Matthew & Toriola, 2024, Bello et al., 2024, Olowe et al., 2024). Strengthening stakeholder collaboration will foster trust and shared ownership of interoperability initiatives.

Finally, integrating transformative technologies such as AI and blockchain will enhance the intelligence, security, and scalability of data exchange systems. Together, these efforts will enable the creation of a truly interoperable health information ecosystem—one that improves patient care, drives clinical innovation, supports public health, and respects the rights and dignity of individuals (Akinade et al., 2025, Ekeh et al., 2025).

9. CONCLUSION

This critical review of health data interoperability standards—focusing on FHIR, HL7, and related frameworks—has highlighted both the progress and persistent challenges in creating connected, efficient healthcare ecosystems. The analysis revealed that while HL7 v2 laid the groundwork for data exchange and FHIR represents a significant leap forward in terms of modularity, web integration, and developer accessibility, fragmentation, inconsistent implementation, and semantic variability continue to impede true interoperability. The review also emphasized the role of standardized terminologies like SNOMED CT and LOINC, the importance of robust data governance, and the necessity for global alignment of policies and practices. The need for interoperable, patient-centric data systems is more urgent than ever. As healthcare delivery increasingly spans multiple providers, technologies, and jurisdictions, seamless, secure, and meaningful data exchange becomes essential not only for continuity of care but also for empowering patients to participate actively in their health journeys. Interoperability supports better clinical outcomes, facilitates population health management, reduces administrative burdens, and enables more responsive public health systems. To achieve this, data systems must be designed to prioritize patients' rights, data integrity, and the ability to share information without sacrificing privacy or security.

Advancing interoperability in healthcare will require sustained collaboration, policy reform, and technological innovation. Stakeholders must work together to harmonize standards, enforce open APIs, and embrace new tools such as artificial intelligence and blockchain to enhance system capabilities. While no single standard offers a complete solution, a strategic integration of the best aspects of existing frameworks, underpinned by patient-focused governance, offers a promising path forward. Only through collective effort and commitment can we build an interoperable health ecosystem that truly meets the demands of 21st-century care.

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