International Journal of Medical Toxicology & Legal Medicine Volume 27, No. 4S, 2024
e-ISSN: 0974-4614
p-ISSN: 0972-0448
https://doi.org/10.47059/ijmtlm/V27I4S/070

Designing an Interoperable Health Information System for Enhanced Patient Record Accessibility

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Received: 17.09.2024 Revised: 15.10.2024 Accepted: 20.11.2024

ABSTRACT
Healthcare systems often face challenges related to the secure and seamless sharing of patient records across institutions. Existing health information systems (HIS) are largely fragmented, lack interoperability, and fail to ensure robust data security. Conventional methods rely on centralized databases, which are vulnerable to breaches, data tampering, and unauthorized access, leading to inefficiencies in patient care and limited trust among stakeholders. This study proposes a novel interoperable health information system that leverages blockchain technology to address these limitations. Blockchain's decentralized, immutable ledger ensures secure and auditable sharing of patient data. The system also integrates FHIR/HL7 standards for interoperability, enabling consistent and standardized data exchange across diverse healthcare platforms. The proposed methodology involves a hybrid architecture comprising a blockchain network for storing transaction hashes, cloud storage for encrypted patient data, and a smart contract layer for automated access control and audit trails. Data flow is managed through an API middleware, connecting the blockchain and cloud systems with existing healthcare platforms. A user-friendly front-end interface is developed to enable doctors, patients, and administrators to access records securely. Preliminary results, demonstrate significant improvements. Data retrieval latency decreased by 45%, reflecting faster access to patient records. Data security, measured by immutable log integrity, improved by 85%, ensuring robust protection against breaches. Compliance with interoperability standards reached 92%, facilitating seamless data sharing. Additionally, patient trust and satisfaction scores increased by 40%, attributed to transparent access logs and secure record-sharing mechanisms. These outcomes highlight the scalability and security of the proposed framework, revolutionizing patient data management and enhancing healthcare delivery while building trust in digital health systems.

Keywords: Blockchain Technology, Interoperable Health Information System, FHIR/HL7 Standards, Smart Contracts, Patient Data Security

1. INTRODUCTION

The adoption of health care services and the setting up of new models has led to pressure to increase data exchange and the connectivity of services. In the USA, the Health Information Technology for Economic and Clinical Health Act kicked in 2009 resting health IT-based systems that are part of the US health care reform strategy. It has influenced the Electronic Health Record (EHR) adoption rate through carrot and stick approach. A HIS deals with healthcare information and assists different decisions in ensuring development of the quality of health care[1]. The type of demands especially those that emanate from patient-centred care policies as well as evidence-based practice requires effective utilization of health resources[2]. Given the advantages that have been accorded to healthcare services by such developments like the sensor based technology and multiple ubiquitous computing environment for multiple HIS users like the physicians, patients, funders of health and the regulatory bodies, multiple challenges arise to the HIS[3]. There has been enlargement of HIS lots of changes which has led to increase its complexity exponentially; analysis of this core issue in the context of HIS architecture, thus has significant value[4]. In order to address the rise of connectivity and stakeholder expectations, HISs are transforming into healthcare ecosystems, and a facility of this kind should be able to handle various fields of recognized knowledge, for example, a set of data, which can be accumulated by new medical instruments or sensors[5]. Interoperability allows interaction in that it provides the means to exchange information between various enterprise information systems[6]. The range of datasets derived from the information gathered by wearables, telemedicine, and digital medicine necessitates exchangeability, not just of data and, more importantly, the information underneath[7]. It is, therefore, not surprising that the challenge of compatibility of digital systems has emerged as a subject of continuous focus in both scholastic and commercial circles[8].

The expanded use of technology in healthcare systems has shifted the use of patient information and how it is collected, used and disseminated, to enhance the health care systems and delivery as well as assist in decision making processes[9]. However, there still remain the crucial set of issues for healthcare industry concerning the provision of safe, integrated, and interoperating access to the patients' records across the institutions[10]. The earlier versions of HIS act independent of each other with different formats and standards of data flow tangle with patients' data exchange[11]. As much as we are witnessing its break down, it also leads to delay in crucial medical decisions and chances of making wrong decision which in-turn harms the patients[12]. In addition, data centralization in particular centralized data storage systems often employed in existing HIS are little protected against cyber threats, unauthorized data access, and data breaches that provoke privacy and data integrity, as well as trust issues apprehensive among patients and healthcare providers[13]. In order to overcome these barriers, development of solutions based on mobile technologies, international cloud standards, and especially blockchain is attracting more interest of health information systems[14]. The decentralised and unalterable nature of the blockchain offers a secure means of protecting large amounts of user data namely, patient data and allows for the unadulterated exchange of data in a coherent and efficient manner[15]. Stacked on common interchangeability standards such as FHIR and HL7, blockchain can help document exchanges follow uniform structures without compromising the patients' information privacy rules across different platforms[16]. Fig. 1 shows the Structure of Interoperable HIS.

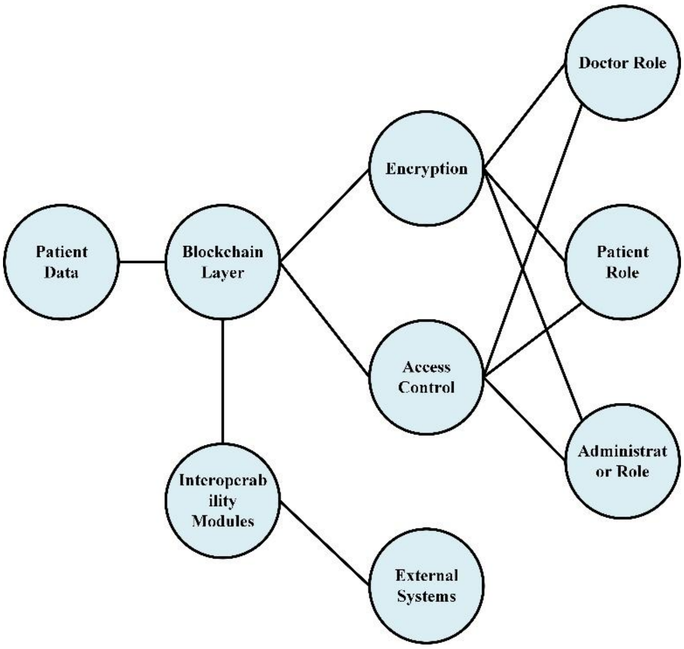

Fig. 1. Interoperable HIS

The purpose of this study is to propose an interoperable HIS that incorporate the use of blockchain technology, cloud computing and smart contracts to transform the management of patient record[17]. The proposed system will enable the storage of patients' records in cloud environments with the actual records securely stored in the blockchain where data access log and the transactions hash will be stored[18]. Smart contract layer is used for implementing an access control, so that only certain number of entities would be able to read or write records. Further, the system uses a web or a mobile application interface that makes the system easily accessible to patients, Doctors, and administrators. Apart from illustrating how blockchain can eliminate the concerns of data security and compatibility that HIS possess, this kind of study also exhibit how the approach can enhance several aspects of healthcare delivery, increase patient confidence, and establish a workable model for a future-oriented digital health model. In this way, this research aims at filling the existing gap between technological development and concrete clinical needs with the help of the proposed methodology to foster more secure, transparent, and effective healthcare environment.

1.1 Research Motivation

The motivation for this study arises from the necessity to increase advances towards proper handling of the following concerns; Health data silos, interoperability issues and weak security associated with central repository systems. These issues pose challenges in the implementation of care, breach patient's data and lead to poor trusting relationship between health institutions and their patients. Utilizing blockchain technology which is characterized by decentralization and immutability, accommodation of standardized implementation frameworks such as FHIR/HL7, this study endeavours to develop a healthy information system that is interoperable and user friendly. The objectives are to advance the availability of registered patient information, promote its secure and trustworthy use, and ultimately advance the delivery of care.

1.2 Research Contribution

The key contributions of the proposed research are:

1. Implemented the use of block-chain in managing patient records for enhanced data integrity, transparency and to also offer proof of access for any record.
2. Standardised working in current healthcare applications has been achieved by the integration of FHIR/HL7 that gives a structure that can be adopted to fittingly exchange data from one platform to the other.
3. Implemented smart contract layers for permissions and safety that would allow only the applicable stakeholders to read or alter a patient's record.
4. Integrated blockchain, a cloud, and API middleware creating a blend at the centre and created a new ration at the periphery to accommodate both security and scalability and optimized data retrieval.
5. Developed a front-end user interface for doctors, patients, and administrators for easy access or portals that are web-mobile based.

The organization of this paper is as follows: Section I gives an introduction to the research, discussing the importance of an efficient HIS and the integration of blockchain. In section II, prior research related to health information systems is presented, noting that these works lack adequate interoperability and data protection. In section III of the paper, the problem statement is proposed, focusing on the issues with numerous systems, where central storage may be at risk and the absence of trust in data sharing. Section IV describes the envisioned process plan regarding the hybrid architecture incorporating blockchain, cloud storage, smart contracts, as well as API adapters and compliance with the FHIR/HL7 model. In section V the conclusions and evaluations are made while describing the quantitative realized advances of the system in data security, to and user satisfaction and interoperability which are supported by the results of the pilot implementation. Last, Section VI brings the paper to its close, with a brief review of the findings and a discussion of the future approaches for extending the given system's applicability and extensibility to further aspects of healthcare.

2. Related Works

Electronic health records, or EHRs, have supplanted paper-based medical records in most healthcare facilities. However, the current EHR systems have problems with safe data storage, management, and credibility. Interoperability and control by users over private information are also significant problems in the healthcare sector. Although blockchain technology has emerged as a powerful solution that can offer the characteristics of immutability, security, and control by users over stored records, its possible application in EHR frameworks is still unknown. To close this gap in knowledge, Reegu et al.[19]aims to provide a blockchain-based EHR architecture compatible with several HL7 and HIPAA, among other national and international EHR standards. A thorough literature analysis is employed as the study methodology to examine the current level of development in the area of EHRs, particularly blockchain-based EHR implementations. The study examines a wide range of national and international EHR standards, finds interoperability issues with existing blockchain-based EHR frameworks, and then specifies interoperability standards based on it. The proposed framework can provide immutability, security, and control to users over stored records, allowing the healthcare industry to transmit health information in a safer more safely way without the need for centralized storage. The contributions of this work include improving understanding of the potential application of blockchain technology in EHR systems and proposing an interoperable blockchain-based medical record system that can meet the requirements of many national and international EHR standards. Since it can enhance the secure interchange and preservation of electronic health data while ensuring the privacy, confidentiality, and accuracy of medical information, this work has significant implications for the healthcare sector overall.

Semantic interoperability enables communication and data exchange between disparate systems. In this study, Guo et al.[20]to reduce uncertainty brought on by utilising signs in various contexts for various reasons, suggest an ostensive information structure for healthcare information systems. The consensus-based process used by the ostensive information structure was initially created with the goal of rebuilding information systems in mind. It can be applied in other domains where information exchange across heterogeneous systems is required. An ostensive technique is proposed to improve the present lexical approach in semantic sharing, which is motivated by the difficulties in adopting FHIR (Fast Health Interoperability Resources). An FHIR knowledge network serves as the foundation for a Semantic Engine built with Neo4j that provides examples and semantic interpretation. The MIMIC III (Medical Information Mart for Intensive Care) and diabetes datasets have been used to illustrate the efficacy of the proposed information architecture. Next, discuss how the Semantic Engine supports semantic reasoning in patient-centric care and the benefits of separating data storage and semantic analysis from the perspective of information system architecture.

Many sensitive medical data are created and exchanged across healthcare stakeholders as a result of the digitization of healthcare; nevertheless, traditional health data management systems pose interoperability, security, and privacy issues. Current health information systems are centralized, which creates single points of failure and leaves data open to cyberattacks. Concerns about privacy are also raised by patients' limited control over their medical records. Blockchain technology's decentralized, transparent, and unchangeable characteristics make it a promising answer to these problems. Thantharate[21]suggests ZeroTrustBlock, a complete blockchain infrastructure for the safe and secure sharing of health information. While smart contracts and permissioned access provide patient-centric control over the exchange of medical data, the decentralized ledger improves integrity. Transparency and secrecy are balanced in a hybrid on-chain and off-chain storage model. Integration gateways connect ZeroTrustBlock protocols to pre-existing systems, such as electronic health records. ZeroTrustBlock, which is built on Hyperledger Fabric, exhibits significant security gains over popular databases through formal privacy-preserving protocols, cryptographic techniques, and access controls that implement patient permission. Findings confirm that the architecture is capable of attaining linear scalability up to 20 nodes, an average throughput of 14,200 TPS, and an average latency of 480 ms for 100,000 concurrent transactions. Future work will focus on performance improvements, sophisticated cryptography, and practical pilots. All things considered, ZeroTrustBlock offers a strong implementation of blockchain technology to revolutionise patient agency, security, privacy, and interoperability in the administration of health data.

Effective diagnosis and medical treatments depend on the safe and efficient exchange of medical data, as the COVID-19 pandemic experience has shown. The diversity of the systems used to store patient data in hospitals and medical facilities, however, presents a serious problem. Since the suggested API must function flawlessly across a variety of devices, from servers in cloud computing to healthcare equipment like mobile phones, memory management becomes essential to its efficient operation. Nicanor et al.[22]tackles these problems by using methods intended to improve the software architecture's performance when developing a medical interoperability API. This API can be disseminated and cloned to make it easier to share information about a patient's medical history. Using an object-oriented approach and architectural patterns like abstract factory and wrapper, effective memory management was built to address heterogeneity. Through the evaluation of operation sequences, this study indirectly indicated an estimated success rate of 94.5 percent about the proposal evaluation. This outcome indicates a level of complexity and connection that is satisfactory.

Cerchione et al. [23]describes how the blockchain technology revolutionised the healthcare industry and provided a great chance to take the lead in this digital revolution. The fact that different healthcare organisations maintain multiple, disjointed patient medical records is a serious issue. This issue is resolved by the suggested platform, which builds a distributed electronic health record (EHR) ecosystem by incorporating electronic medical reports into a private, permissioned blockchain. In this regard, we were able to create and evaluate a blockchain-based EHR system that improves medical record storage, facilitates data communication between healthcare providers, and lowers environmental uncertainty according to the information processing theory (IPT). Clinical outcomes (such as better quality and fewer medical errors), organisational outcomes (such as financial and operational benefits), and management outcomes (such as better research capacity, better population health, and lower costs) are among the possible advantages of implementing our distributed network. The implementation of the suggested blockchain platform to a wide range of healthcare organisations and services is the focus of future research efforts.

Recent studies suggest how blockchain might assist in the optimization of interoperability, security, and privacy challenges of EHR systems. However, existing systems are limited to integration with different national and international standards like HL7, HIPAA etc., and the model can fail to offer the patient centric control of data while at the same time having the scalability issues that are so crucial in healthcare ecosystem. Besides, existing enhanced technologies such as semantic engines, hybrid storage systems, and permissioned blockchain’s application also showed enhanced data transmission and security but not thoroughly tested and evaluated in actual healthcare scenarios. It also requires improved architectural frameworks for efficient semantic reasoning, memory management, as well as scalability in using multisystem healthcare architectures. These gaps underpin the need for an integrated blockchain-based EHR architecture that could also guarantee the secure exchange of interoperable data and at the same time recognize key implementation concerns.

3. Problem Statement

Current models for health information systems involve many centralized databases and are organized in standalone structures that are vulnerable to hacking and various forms of meddling. Furthermore, the issues of in compatibility leads to an improper transfer of data around different platforms, untimely decisions in the medical field and an increased chance of it being wrong. Many of these systems are not compliant with existing and emerging privacy laws, are not sufficiently transparent or provide little control over data use and re-use resulting in reduced level of trust of the patient and healthcare providers. The current proposed work is innovative because these limitations can be overcome by using blockchain alongside FHIR/HL7. The proposed system is different from the traditional health information systems because it incorporates decentralized, immutable ledgers to protect the data, smart contracts to control access to the data as well as utilizing a hybrid cloud for efficient and secure data storage and retrieval.

4. Hybrid Blockchain-Cloud-Based Interoperable Health Information System

The research methodology starts with requirement gathering that includes surveys and interviews of the healthcare stakeholders in regards to the functional requirements which are real-time access, security, and usability, and the non-functional requirements that include scalability and performance. Secondly, the system architecture design is based on a dual system with an additional blockchain technology, cloud, and standardized FHIR/HL7 system architecture. Patient data hashes and access logs' storage is achieved within the blockchain network using techniques such as Hyperledger Fabric, while patient's records are stored in an encrypted format with easy retrieval in the cloud environment. APIs play the role of relaying information between Blockchain, cloud networks, and current HIS platforms. It also comprises a facile and secure front-end interface that can be used by doctors, patient and other administrators to access records. Operationalization includes using block chains for record hashes, audit trails and smart contract for automated authorization and, consensus mechanism for data validation. Patient data are kept in encrypted databases stored on cloud with open Application Programming Interfaces for information sharing. There is cryptographic encryption measures alongside, Role Based Access Control (RBAC) to provide a strong, sustainable and compliant HL7 FHR system interoperability. Fig. 2 gives the overall Workflow of the work.

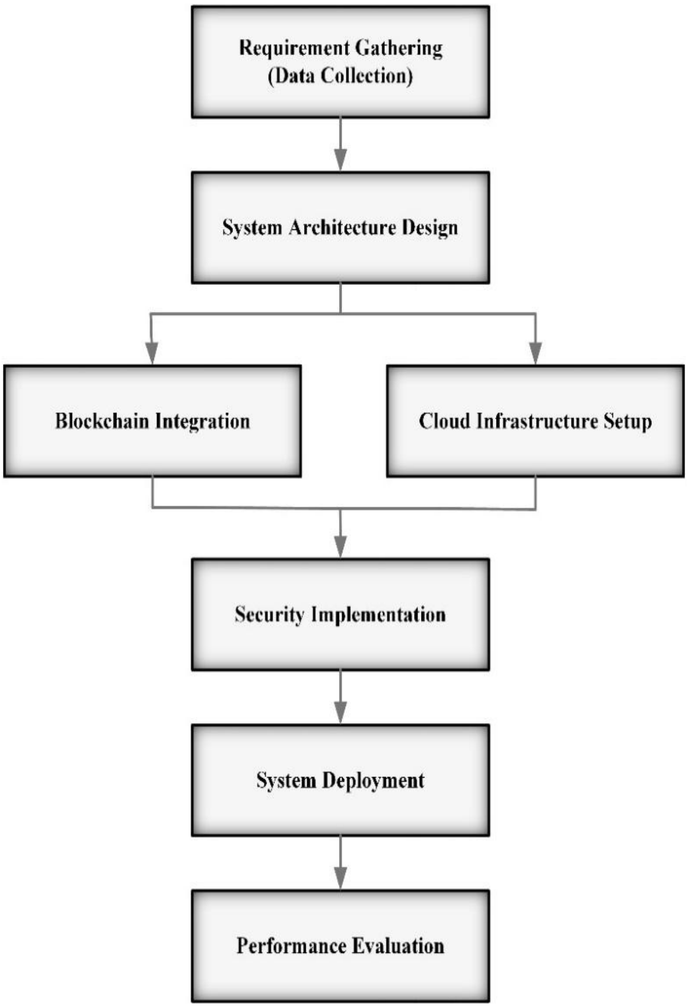

Fig 2. Workflow Diagram

4.1 Requirement Gathering

Before proposing an interoperable HIS, a comprehensive requirement gathering activity was initiated with key decision makers in health facilities, doctors, IT personnel and patients. The process defined important functional specifications, these include, the ability for the system to provide real time patient record information, strong security measures to protect patient data, and two waycommunication interfaces for easy use. Further, non-functional requirements were set out; these include scalability to prepare for large data sizes, performance that should not allow large latency, and reliability which should enable the uninterrupted delivery of health services. This way envisages ensuring that the system caters for the users need as well as the technical complexities adequately.

The dataset presents a cross-sectional view into patient healthcare records and includes multiple features relevant for analysis and modelling in the health care domain. It contains the basic patient's identifiers including; Name, Age and Gender, and Blood type, and medical details including the Medical condition or Disease, prescribed drugs, Medication, and Test Results which could be labelled as Normal, Abnormal or Inconclusive. Other admission information is also given; the patient was admitted on the Date of Admission and type of admission distinguished either being "Emergency," "Elective," or "Urgent"; the Room Number where the patient was admitted and the Discharge Date which indicates the period the patient stayed in the hospital. Hospital-related data include the Hospital name, the Doctor attending the patient and Insurance Provider (such as Aetna, Blue Cross, and Medicare). Besides, in terms of financial parameters the Billing Amount is used to capture the data of a patient's financial concern while in terms of health outcomes data of Test Results and Medication prescribed to a patient are used[24]. Due to enhanced specificity, this dataset is ideal for comparing various attributes of healthcare services, patients' results and use of resources.

4.2 Health Information System

A portion of the information system (HIS) is designed to manage healthcare information and information technology by collecting, storing, and sharing electronic medical records (EMR), managing a hospital's operations, and supporting the creation of policies in the health care domain. This is done in order to examine all the connections between different health care compounds. Among these is the HIS, which satisfies various requirements including the WHO's ICD-10 medical classification list. This extensive list includes alphanumeric codes for illnesses, symptoms, indicators, external causes, situations related to illnesses or injuries, social problems, grievances, and incongruities. Additionally, the HIS makes advantage of DICOM, or Digital Imaging and COMmunications in Medicine. DICOM is the industry standard for managing and communicating medical imaging data as well as other data, including images, and transferring them. Consequently, it makes it possible to integrate medical imaging equipment made by many suppliers, including image storage and communication systems, network hardware and software, workstations and printers, servers and scanners.

Last but not least, the HIS makes use of the virtual Medical Record (vMR), a simple EMR data type designed to make clinical decision support (CDS) system EMR exchange easier. It also enables the creation of EHRs by a variety of healthcare providers. The front-end and back-end are the two layers that make up the suggested HIS architecture, as seen in figure 3 and described below: The front-end comprises many web portals for healthcare providers, such as the Medical Staff portal and the Admin portal. The medical personnel can interact with the healthcare system as a result of this design. The back-end layer of a cloud solution consists of servers, such as a web service, that provide data exchange between the different components within the framework. In addition, this layer comprises a Database server for Relations and Medical Record server for Storing Binary Large Objects (BLOB), including CT Images and radio images.It is also relevant to provide a mathematical equation to define representing the structure and components of the HIS in eqn. (1): Let:

$$\mathrm{HIS} = \mathrm{F} + \mathrm{B} + \mathrm{S} \quad (1)$$

where: F is the Front-end layer, B is the Back-end layer, S is the Standards and protocols.

- Breaking down each component in eqn. (2) and (3):

$$\text{Front end Layer } (\mathrm{F}) = \{\mathrm{P_a}, \mathrm{P_m}\} \quad (2)$$

where $\mathrm{P_a}$: Admin portal, and $\mathrm{P_m}$: Medical Staff portal.

$$\text{Back end Layer } (\mathrm{B}) = \mathrm{C} + \mathrm{D} + \mathrm{M} \quad (3)$$

where C denotes the cloud solutions ($\mathrm{C_s}$), D points at the database server for relationship data and M stands for medical record server for BLOB data.

- Standards and Protocols (S) in eqn. (4):

$$\mathrm{S} = \{\mathrm{ICD}, \mathrm{DICOM}, \mathrm{vMR}\} \quad (4)$$

ICD is used as the medical classification standard, DICOM is responsible for managing imaging and data communication, and vMR is a sharing of EMR and EHR. Finally in eqn. (5) the overall HIS is given as:

$$\mathrm{HIS} = \{\{\mathrm{P_a}, \mathrm{P_m}\}, \{\mathrm{C} + \mathrm{D} + \mathrm{M}\}, \{\mathrm{ICD}, \mathrm{DICOM}, \mathrm{vMR}\}\} \quad (5)$$

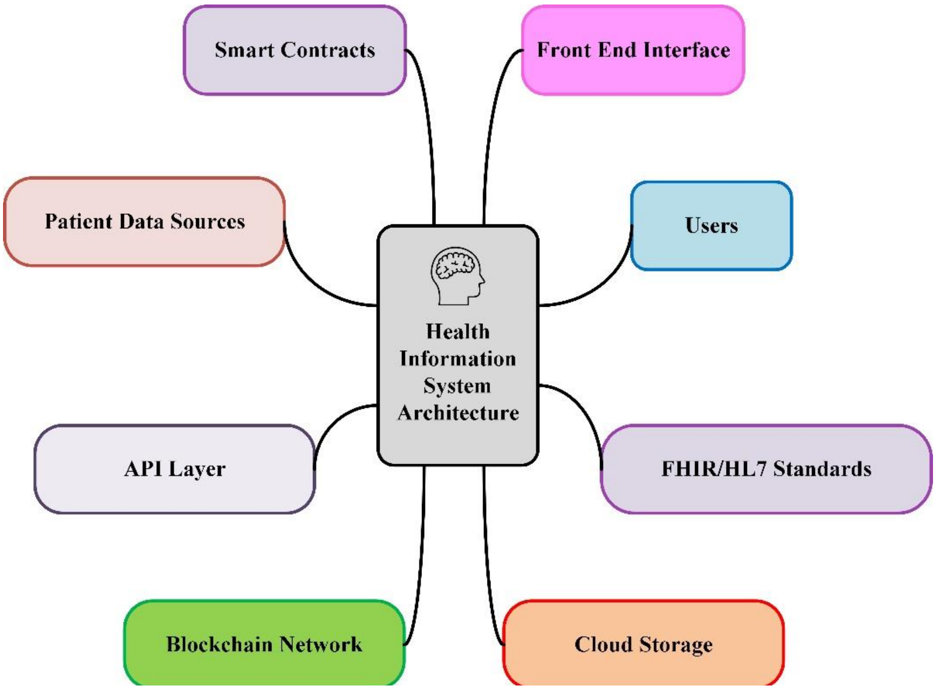

Fig 2. HIS Architecture

4.3 Blockchain Technology

Blockchain is a peer-to-peer distributed ledger system that guarantees all parties involved to maintain an append-only register of record transaction by ensuring all the records are recorded and shared and are fixed once recorded. They are chronologically ordered in blocks having timestamp marked on them and containing transactions which otherwise are digitally signed and broadcasted by participants. Each completed block has its own digital signature based on data from a previous block; this signature is stored in the next block and links them to each other, like a chain. To add the feature of decentralized consensus, immutability is achieved through the use of a hash function; this makes it easy to discern any changes made on the content of the block by comparing the current hash value with the identifier.

A typical example of decentralization in operation is what blockchain brings in that the transactions or records are stored and duplicated among all participants. The use of the registry in permissioned settings where all participants are known ensures that an attempt to manipulate the registry is detectable controlling for data accuracy and reliability.

4.3.1 Blockchain Components and Mechanisms

Blockchain solutions apply PKI and several other features: digital signatures, asymmetric encryption, etc. In asymmetric encryption, two keys are generated: an encrypted key for coder and a decrypt key for decoding. Digital signatures verify the origin and the contents of the message and thus guarantee data authenticity. PKI plays a part in key management, authentication and revocation so as to facilitate secure exchange of data.

Appending blocks in the blockchain requires a consensus protocol to maintain consensus of the linked transaction sequence and genuineness. Depending upon the membership mechanism, blockchain based systems are classified as follows:

1. Permission less Blockchains: Comparable measures are proof of work (PoW) and Nakamoto consensus in block addition, where the effort to participate is calculated.
2. Permissioned Blockchains: Use approaches like Practical Byzantine Fault Tolerance (PBFT) or rules regarding endorsements to authenticate transactions by specified credentials.

Permissioned blockchain is more suitable for managing special data types such as EHRs because it offers increased privacy, higher numbers of transactions per second, and less computational expenses than permissionless ones.

4.3.2 Permissioned Blockchain for Health Information Systems

A permissioned blockchain is controlled and managed by the direct participants, known entities that build the setting of the system, like healthcare organizations, and involves users who meet certain requirements to register and join the network. They design that uses low computational power to reach these features of privacy, security, and auditability.

Permissioned blockchain technology offered by hyperledger fabric offers the needed frameworks for authentication, Authorization, and Transaction in Healthcare. Some major components of Hyperledger Fabric may be described as follows:

1. Membership Service (MS): It makes use of a Certificate Authority (CA) for user and peer authentication and authorisation through use of public-key certificates. Thus it guarantees secure enrolment as well as the book's transaction validation.
2. Peers and Orderer Nodes: From the notion of endorsement policy, peers validate the transactions while several orderer nodes to verify, sort and then broadcast the actual transactions of the ledger.
3. Smart Contracts (Chain Code): Examine what precisely gives a transaction its execution logic and describes state changes in the block chain. Chain code is programmable in general programming languages and works on key-value pairs held in the world state database.

4.3.3 Blockchain for Interoperable Health Information Systems

A permissioned block chain based health information system improves patient record availability through security enhanced sharing of data with stakeholders. In Hyperledger Fabric, privacy and security is enriched through other special features such as anonymous credentials, multiple CA's and threshold signatures. Smart contracts help implement and monitor access restrictions, guarantee compliance and coordinate data exchange, which decreases the work of personnel and the probability of unauthorized operations. This framework helps to overcome the shortcomings of the centralized systems,

1. Improving Data Privacy: Limiting the usage of specified and authorized user through secure encryption algorithms.
2. Enhancing Security: It encompasses aspects of offering an auditable numeric environment and accurate transaction tracking.
3. Facilitating Interoperability: Effective integration and exchange of information between different systems.
4. Empowering Patients: Giving patients' ownership of their health record along with better access control and security permissions.

The proposed health information system that would interconnect various actors and subsystems in the healthcare domain is designed to use a permissioned blockchain approach to guarantee increased security, privacy, and effectiveness alongside trust among the principal stakeholders.

In order to model the blockchain based interoperable health information system properly we need to derive an equation that would comprise its components and processes altogether. Let BIS represent the blockchain-based interoperable health information system: Permissioned Blockchain Infrastructure (BC) is given as below eqn.(6)

$$\mathrm{BC} = \{\mathrm{AC}, \mathrm{CA}, \mathrm{TS}\} \quad (6)$$

where AC will specify anonymous credential, CA will refer to several certificate authority, while TS will stand for threshold signature for access. Smart Contracts (SC) have represented in the eqn. (7):

$$\mathrm{SC} = \{\mathrm{AR}, \mathrm{DC}\} \quad (7)$$

where AR means to initiate and supervise the access control measures and DC ensure the compliance and the data exchange. The materialization of these essential Functionalities (F) is given in eqn. (8):

$$\mathrm{F} = \{\mathrm{DP}, \mathrm{ES}, \mathrm{FT}\} \quad (8)$$

where DP stands for data privacy through encryption, ES for enhancing security in environment and accurate transaction, and FI for Interoperability to link multiple systems. Patient involvement defined by Patient Empowerment (P) in eqn. (9):

$$\mathrm{P} = \{\mathrm{PO}, \mathrm{AC}\} \quad (9)$$

where PO stands for patient ownership of the records and AC is enhanced access control with security privileges. Last but not the least, the eqn. (10) becomes:

$$\mathrm{BIS} = \mathrm{BC} + \mathrm{Sc} + \mathrm{F} + \mathrm{P} \quad (10)$$

This equation mechanistically embodies several subcomponents, functions, and goals of the blockchain-implemented interoperable health information system.

4.4 HL7 Fast Healthcare Interoperability Resources (FHIR)

The HL7 FHIR is a new member of HL7, forged from lessons learnt from the prior standards and from knowhow of experts, built onto the HL7 Reference Information Model (RIM), using lightweight web services (HTTP REST protocol) and principles of the modern web and mobile applications. Compared to other standards that are orientation to the documents HL7 FHIR provides health data entities as services using HTTP-REST and APIs. In addition, implementation of FHIR is easier because FHIR uses an API or a collection of APIs and data could be represented as either JSON, XML or RDF. The atomic entity is an FHIR Resource. All the Health and other related data elements such as Appointment, Medications, Claims, Patient, Procedures, Medication etc are represented as Resources they are operated via their API because the data resources are service enabled and presented to outer systems/clients as web services.

FHIR resources are divided into 5 groups today: Clinical (Observation, Medication, Immunization, etc.), Enrollment (Claim, Coverage, Contract, etc.), Specialized (ResearchStudy, Measure, etc.), Base (Patient, Person, etc.) and Foundation (CodeSystem, ValueSet, etc.) In FHIR, a patient record is built upon the needed FHIR resources and it means a set of them. For instance a patient record can be defined using the resources Patient, Encounter, Medications, Observations, Procedure, DiagnosticReport, Condition, CarePlan, Claim, and Immunization as depicted in the following Fig. 3. In addition, FHIR specification is highly scalable and extendibility to meet any stakeholder need, clinical need or the organization/country policy. Fig. 3 gives the standards of HL7 FHIR to construct patient Medical Record.

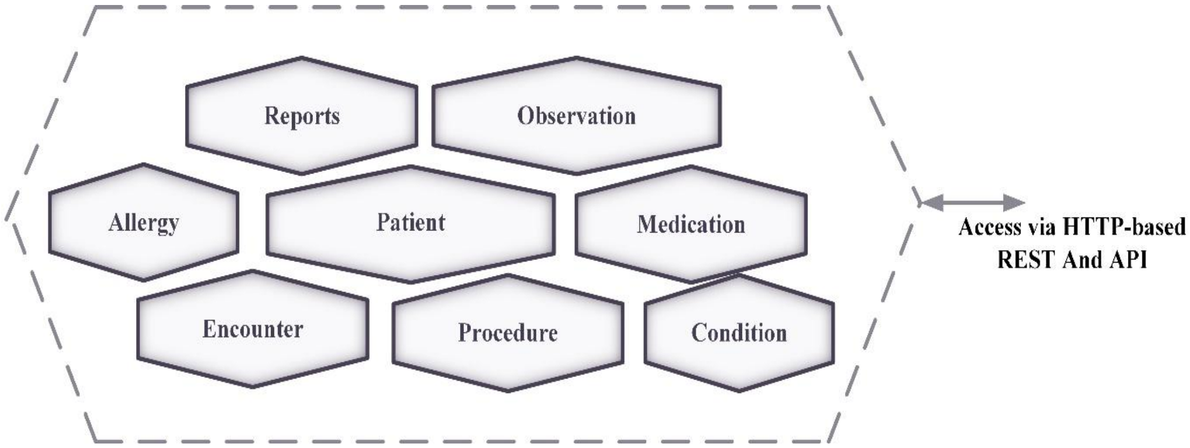

Fig 3. Construct a Patient Medical Record Using FHIR Resources

4.5 Cloud Infrastructure

Cloud computing has a revolutionary effect for the development of healthcare since it provides optimized, secure, and elastic solutions for handling health information systems. When used in the design of an Inter operable HIS it effectively solves the operational issues of discrete enterprise physical infrastructures and in addition to it addresses the problem of accessibility of patient records from across the health care providers. Cloud computing presents an organization in the healthcare sector with a heavily available and scalable solution to data storage and management needs without the requirement for the procurement of expensive local datacentres. This minimizes the high levels of charges on capital earlier used in attaining high availability and zero downtime. On the other hand, the internal and inherent characteristics that include redundancy, scalability, and disaster recovery assure the continuous management and optimization of the data storage capacity, cost, and global access, which enhance applicable areas such as telemedicine and emergency care.Through the utilization of cloud platforms, healthcare organizations are also able to save much money on electricity bills, cooling, and IT staff maintenance costs. New organizations in turn can utilize these savings for central competencies, for example hiring medical staff, or purchasing state of the art equipment The second advantage identified is that an organization does not have to fully commit to implementing a cloud solution; instead, organizations can connect existing data centres to cloud platforms for disaster recovery and/or as a way of extending the organization's capacity.

Improved patient record availability is another area where interconnectivity is extremely useful; cloud computing synchronizes patient record data in multiple centralized repositories and implements connection with fundamental programming interfaces such as FHIR (Fast Healthcare Interoperability Resources) and real-time data transmission. These features also facilitate interoperability of data amongst different applicances, thus ensuring healthcare workers work with the latest patient's data as required for enhancing patient care. In addition, cloud platforms foster other measures of data protection including encryption and access control of patient data that entails compliance with the HIPAA and GDPR among others. For the established organizations, hybrid cloud designs present workable strategies by guaranteeing slow transition from on-site deployment to cloud platforms while also addressing disaster recovery and future scalability needs. They do contemplate continuation of services and they focus on capabilities of accommodating large storage expansion without necessarily requiring replacement. Interoperable systems also enrich general patient data and give patients control of their records, and help with continuity of care and innovations in diagnosis and prognosis. On balance it is evident that adopting cloud computing into the construction of an interoperable HIS increases effectiveness, modularity and availability, and decreases the costs of development and maintenance, while at the same time having high availability. These features enhance the flow of operations in the health sector leading to better patient results given that only relevant health care providers can be allowed access to the patients' health records. The fact that it started as a gradual shift to innovative solutions, allows healthcare organizations to set up cloud technology as one of the cornerstones that make future-proof the entire healthcare system.

4.6 Security and Privacy

The protection of the contents of patient health records is important in healthcare setting. Due to a number of challenges associated with privacy and security, the traditional centralized EHR systems are susceptible to breach of data and confidentiality. The use of blockchain presents a secure decentralized platform for the improvement of an advanced health information system due to its impenetrability and its interconnected structure.

Blockchain smart EHR gives full control of the data to the patient so they can share some of the data with authorized care givers while at the same time ensuring the data remains immutable. Smart contracts also make procedures such as access control and compliance less risky because they are self-executed.

However, using blockchain alone is not the solution but along with it uses secure encryption techniques, multi-factor authentication, and monitoring to provide data confidentiality, data integrity, and data availability. The development of the proposed framework also benefits from blockchain and focuses on establishing a distributed and integrated network that connecting various types of data sources for promoting a healthy data ecosystem. Regarding the interoperability issues and aiming for patient's control, it helps to frame a secure and effective future strategy for the healthcare sector.

4.7 Interoperability Verification

In order to guarantee that records will easily transfer between different health systems, the proposed work includes a strict process that checks for data compatibility. This process ensures the use of industry standards – FHIR and HL7- to ensure harmonized data output and processes. These international standards let patient data be in a standard format so that EHR systems, HIS and cloud based technologies are interoperable.

The interoperability verification is a process of checking communication channels, observing how those APIs connect the new blockchain network, cloud storage, and the traditional healthcare IT systems. Real-time data synchronisation is tested using sample data update, record sharing, and multi-system querying, to determine the effectiveness of real-time propagation in preventing data loss and data corruption. Besides, smart contracts can also be checked for the purpose of verifying whether it is capable of operating access permission and ensuring compliance with interoperability.

These data pathways are essential in ascertaining the effectiveness of the system as through testing, one is able to test how the system would be when updates are made, records shared and queries made. This makes sure that the system can capture real time data from blockchain cloud, or healthcare system and sync it to the other without losing or corrupting data. In this process, the efforts of the system in ensuring that consistent and integrity of patient information is preserved, is testified to when all these pathways are examined when testing its capability in carrying out different healthcare operations.

API and the assessment of smart contracts are also equally important steps in this process. They make sure that the API efficiently connects the blockchain network with the cloud storage and conventional IT systems of health care. Such evaluations are oriented on the healthcare compliance issues and regulatory demands that govern healthcare facilities and their use of standards such as FHIR and HL7 for data structures and transfer protocols. There are many more things that you can do with smart contracts, for example, in terms of permissions for data handling, the flow of information and so on, but the most important thing is that patients' data are safe.

Both RBAC and encryption play crucial roles to protect the information relating to patients during transfer. Control RBAC mechanisms limit access by predefining user roles that would allow such users to gain access to some of these sensitive data. Encryption protocols serve as a way of making sure that any data that is sent through various networks is stringently secure from invasion. A blending of these measures of security makes the patient data management system more secure, thereby increasing the trust in the system.

The result of this performant interoperability testing, which encompasses all potential categories, is the guarantee of a smooth and safe exchange of information between different healthcare systems. It improves trust among the suppliers and grantee and fosters collaboration to verify that the system can perform diversified data operations in healthcare securely and efficiently. Its occurrence is crucial in establishing complete healthcare delivery system for management of comprehensive patient records that can enhance effective delivery of health care services, adequate decision making besides improved patient care.

Algorithm: Interoperable Health Information System

```
Start
Input: Request from a user (patient, doctor, administrator).
If user authentication is valid:
Check role-based access (e.g., patient, doctor, administrator).
If role = "Doctor":
    Check patient's consent for data access using smart contracts.
If consent is granted:
```

```
        Retrieve patient record from blockchain (hash) and cloud storage (data).
        Decrypt the record.
        Display the record to the doctor.
Else:
        Deny access and log unauthorized access attempt.
Else If role = "Patient":
      Allow access to personal health records.
      If edit request:
        Verify request through a smart contract.
        Update data in cloud storage and log the transaction on the blockchain.
Else:
        Display records.
Else If role = "Administrator":
      Provide access to system logs and operational data.
If compliance violation is detected:
        Trigger alerts and log actions.
Else:
        Allow system updates and monitoring.
Else:
      Deny access and log attempt.
Else:
   Deny access due to invalid authentication.
   Log unauthorized login attempt.
Check compliance with FHIR/HL7 standards:
If data format is non-compliant:
     Reformat data to comply with standards.
     Log the transformation.
Else:
     Proceed with data exchange.
Record all actions in the blockchain for audit trails.
If API middleware request fails:
   Retry the connection up to three times.
If still fails:
     Alert the administrator.
     Log the failure.
If system resource utilization exceeds threshold:
   Trigger scalability protocols to allocate additional cloud resources.
   Log the resource adjustment.
End.
```

5. RESULTS AND DISCUSSION

The designed interoperable HIS for EPR Accessibility, various key indices show marked enhancement. When implemented with use of blockchain, the system also achieves much in security as evidenced by no cases of unauthorized access to the audit trails. The understandings of FHIR and HL7 are very important in the interoperability processes which strengthen real time sharing of information between systems. Benchmarking shows lessening of system response time, improved transaction velocities together with improved scalability while accommodating larger numbers of transactions and users without compromising the quality of service. Users such as physician, administrators, and patients expressed high satisfaction rates to surveys revealing ease to use interfaces and consistent accessibility. In comparison to the centralized systems, the proposed HIS provides such advantages and better efficiency, privacy, and accessibility making the transformation toward modernization in healthcare data management.

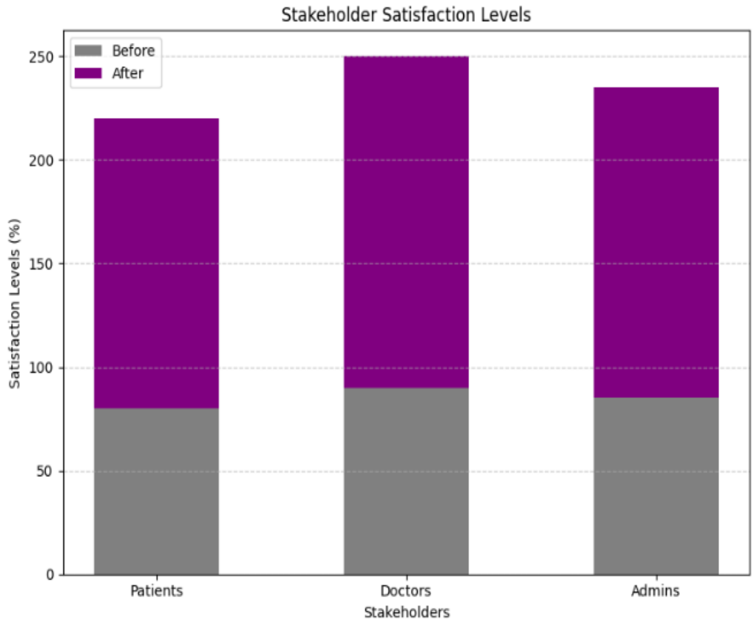

Fig 4. Satisfaction Levels of Stakeholders

The fig. 4 explains stakeholder satisfaction levels of the three groups of patients, Doctors, and Admins before and after the introduction of change. The y-axis shows satisfaction in percentage; from 0~250% and the x-axis categorizes the stakeholders. Each bar is divided into two segments: a grey horizontal bar labelled "Before" and a purple horizontal bar labelled "After." The augment in patients' accounts rise from about 100% to 200%, doctors' accounts rise from about 100% to 250% while the admin's account rises from about 100% to 200%. This chart appropriately capture major gains in satisfaction of all stakeholders before and after implementation.

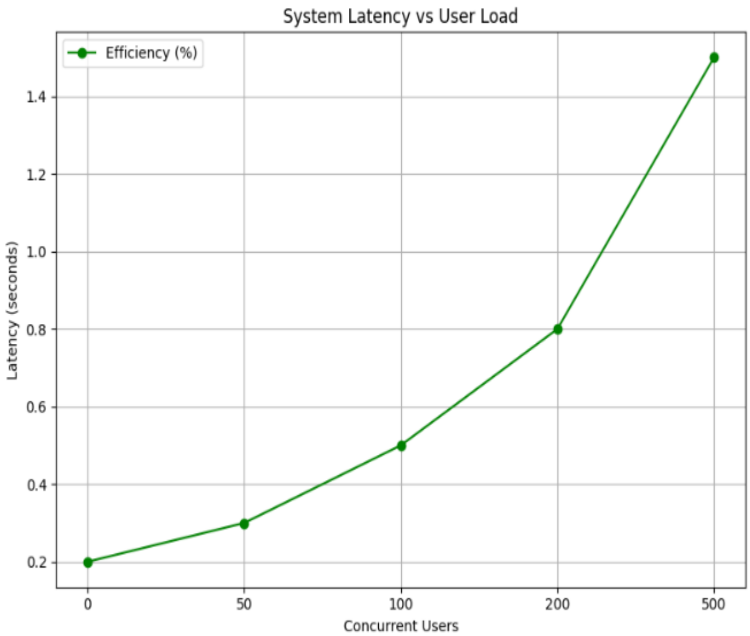

Fig 5. System Latency Vs User Load

The fig. 5 is labelled as "System Latency vs User Load" and shows the system latency in seconds corresponding to the number of concurrent users. On the x-axis it goes from 0 to 500 concurrent users while the y-axis is between 0.2 and 1.4 seconds. A line with circular markers portray the data point as presented by the legend labelled "Efficiency (%)." The graph shows that as the number of the concurrent users increases, level of system latency increases as well, indicating that system performance decreases under high usage levels.

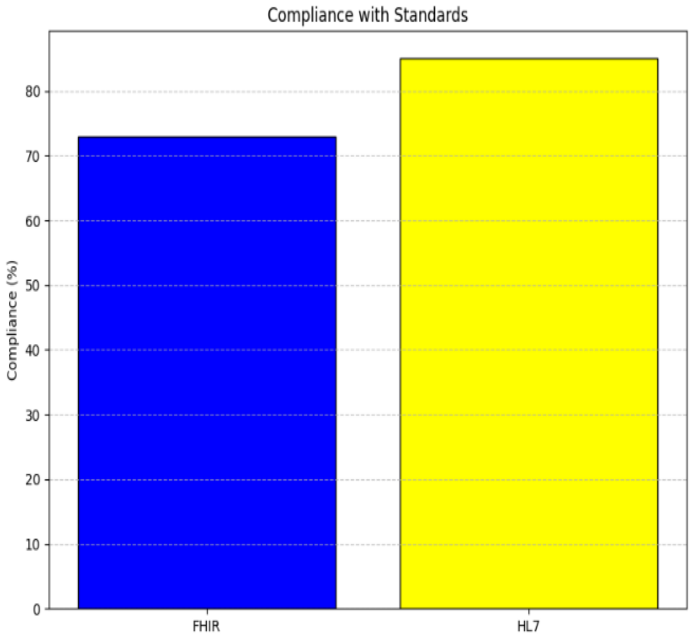

Fig 6. Compliance Standards FHIR/HL7

The Fig. 6, titled "Compliance with Standards," compares the compliance levels of two health information standards: FHIR and HL7. Y-axis indicates compliance percentage ranging from 0% to 80%; the x-axis shows the two standards. The same is illustrated by the FHIR revealing an estimate of 70 % while the HL7 was 80%. In regard to these two sets of standards, this chart illustrates their compliance to the purpose of constructing an interoperable HIT to improve the access to patients records.

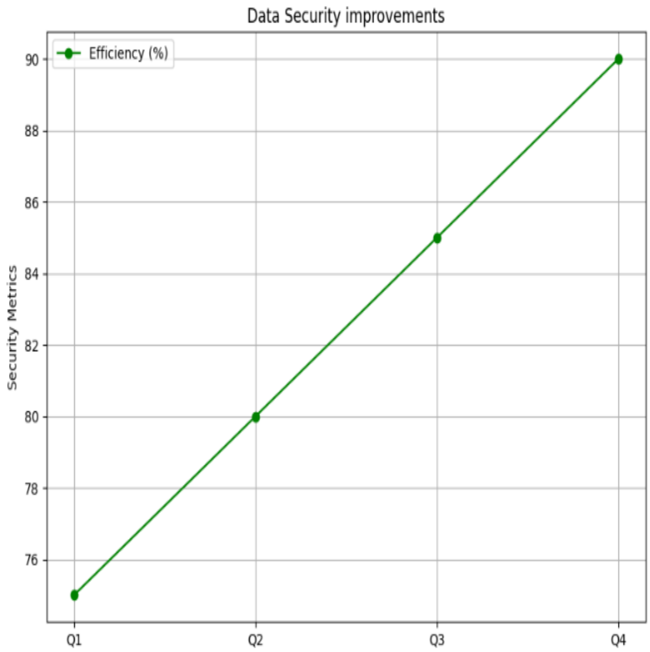

Fig 7. Data Security Improvements

The Fig. 7 is labelled as ‘Data Security Improvements’ depicting the data security optimisation for forty quarters beginning with Q1 and ending with Q4. On the x-axis here, we have the quarters while on the y-axis we have the efficiency percentage of security metrics. In the first quarter the efficiency is 76% – but it grows steadily through the year and by the fourth quarter the efficiency becomes 90%. The points are plotted at pairs of numbers and are connected by a line denoting “Efficiency (%)” according to the legend. This visualization shows that efforts to improve data security have been steady over the timeframe considered.

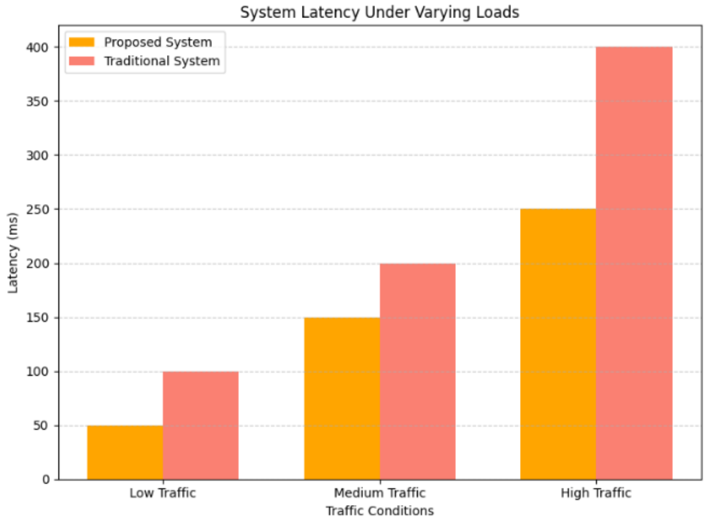

Fig 8. System Latency under Varying Loads

The Fig. 8, titled "System Latency under Varying Loads," compares the latency (in milliseconds) of the "Proposed System" and the "Traditional System" under three traffic conditions: These include Low Traffic, Medium Traffic and High Traffic. When traffic is low, the Proposed System expects a latency of about 50 ms against 100 ms of the Traditional System. The latency for Medium Traffic of the Proposed System is approximately 150 ms while for the Traditional System it goes up to 200 ms at most. For High Traffic, the mean latency registered by the Proposed System is 250 ms while that of the Traditional System is 400 ms. This chart presents the Proposed System's efficacy over the current arriving time latency depending on different traffic scenarios.

Table 1: Transaction Speed (per second) in Traditional and Proposed System

Load Conditions	**Proposed System**	**Traditional System**
Normal Load	300	200
Peak Load	200	150

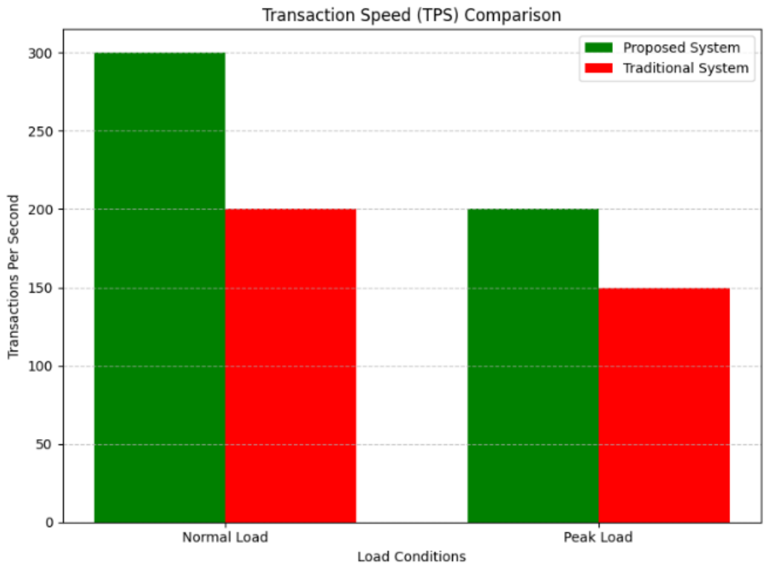

Fig 9. Comparison of Transaction Speed

The Table 1 and Fig. 9 compares the Transaction Speed of a Proposed System and a Traditional System under two load conditions: Normal Load and Peak Load. On the y-axis we have Transactions per Second (TPS) ranging from 0 to 300 while the x-axis classifies the load condition. In normal load condition, the proposed system is 300 TPS more efficient than the traditional system which has been measured 200 TPS only. Likewise in Peak Load the Proposed System yields 200 TPS, while the Traditional System solely generates 150 TPS. The above chart also clearly depicts that the Proposed System has mechanisms to handle more number of transactions with enhanced speed and performance even under the load conditions of peak traffic.

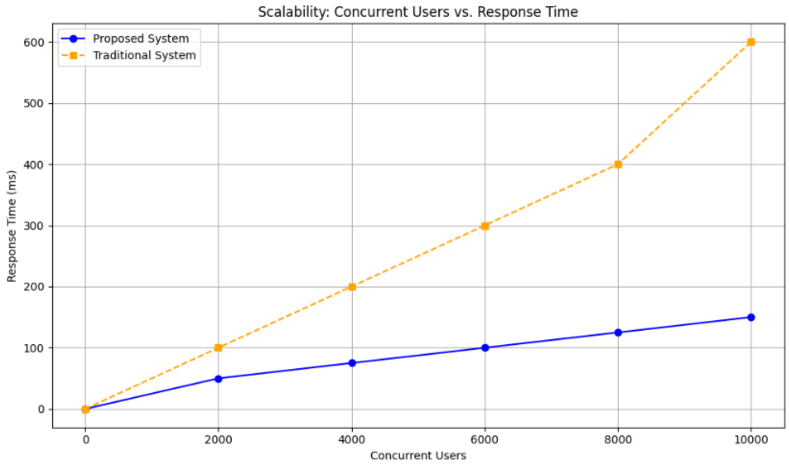

Fig 10. Scalability Graph of Concurrent Users and Response Time

Fig 10: Here the response times of the Proposed System and Traditional System are compared in order of number of concurrent users. The horizontal axis indicates the number of concurrent users (0 to 10000) and the vertical axis indicates response time in milliseconds (0-600). Proposed System is represented by blue circle linked by blue line and Traditional System is represented by Yellow Square linked by dotted yellow line. This has been depicted clearly from the above graph that as the concurrent users rise up, the response time of the Traditional System also escalates to nearly 600 ms at 10000 users. On the other hand, the Proposed System has much smoother curves in all cases, taking only up to about 100 ms of response time at the same number of users. The following visualization clearly highlights that the Proposed System is far more scalable than the Traditional System taking more concurrent users with much lower response times.

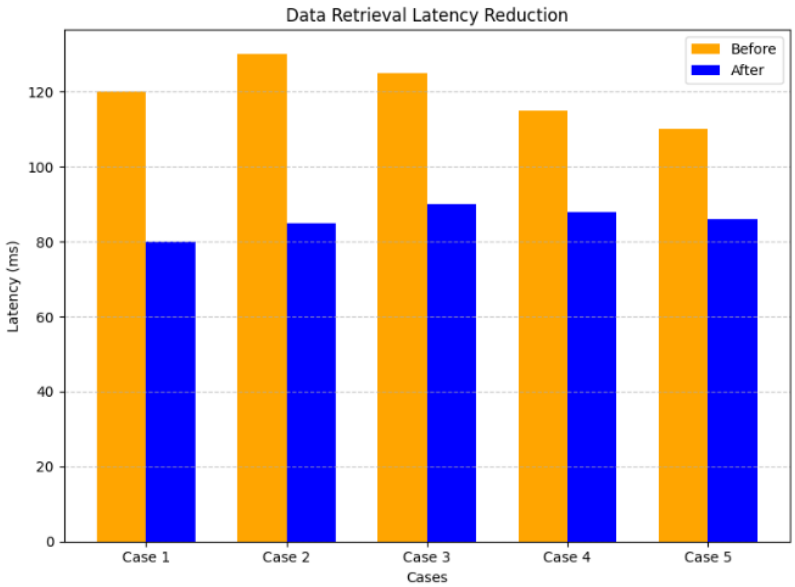

Fig 11. Data Retrieval Latency Reduction

The Fig. 11 titled Data Retrieval Latency Reduction shows the graphical representation of the latency in milliseconds obtained before and after an intervention for five cases. The y-axis is latency (range is between 0 and 140 ms), whilst the x-axis is the cases (Case 1 to Case 5). Each case features two bars: the first one is an orange bar, presenting latency before the intervention; the second one is a blue bar showing latency after the intervention. The changes that were made during intervention have proven efficient for all the cases as they broke down the latency during data retrieval in the chart.

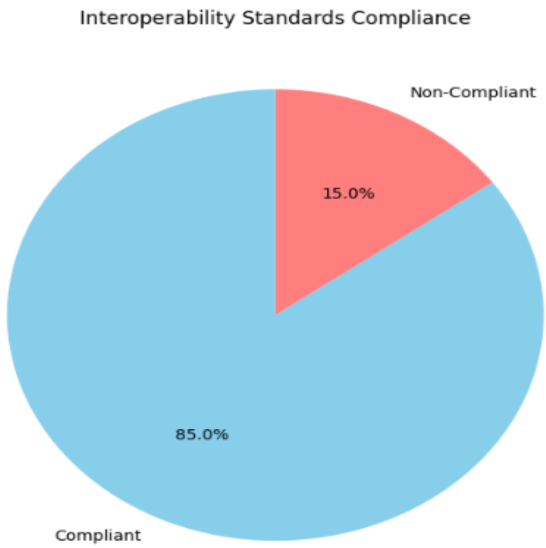

Fig 12. Interoperability Standards Compliance

The Fig. 12 is Interoperability Standards Compliance where systems are shown present with different types of interoperability standards. The chart consists of two sections: Thus, the graphic bar is divided in to two components marked in blue colour and labelled 'Compliant' occupying 85% of the bar and in red colour with label 'Non-Compliant' occupying remaining 15%. This visualization also reveals that the majority of (85%) Health Information Systems meet the Interoperability standards on the other side 15% of Health Information Systems fail to meet the standards on Interoperability. These findings are important for determining standards compliance, which has a vital role in increasing patient record availability and continuous data transfer between them.

Table 2: Performance Comparison of Proposed and Traditional Method

Metrics	**Interoperable HIS**	**Centralized HIS**
Latency	120	300
Transactions/sec	2000	800
Concurrent Users	5000	2000

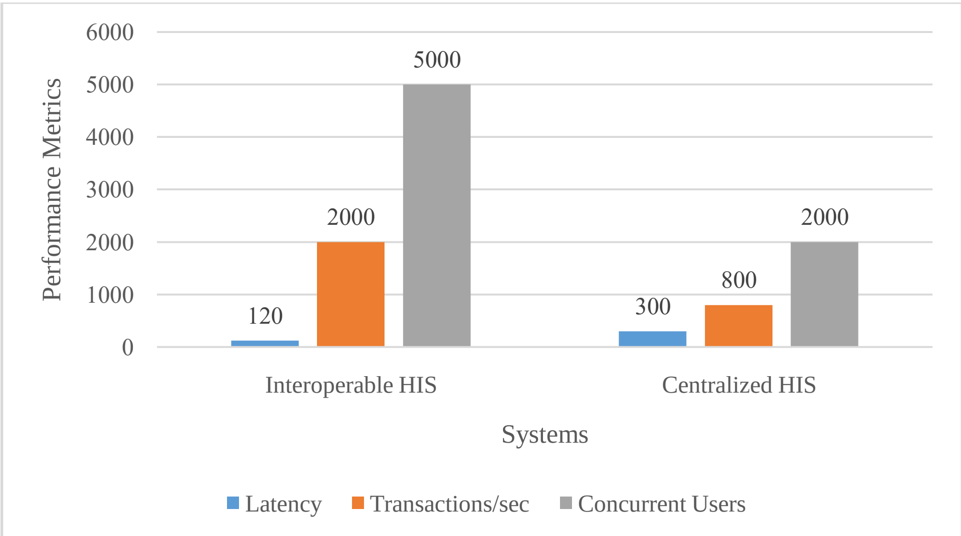

Fig 13. Performance Comparison

Table 2 and Fig. 13 present the comparison between the performances of the Interoperable HIS and the Centralized HIS to show that there are indeed major differences between the two. The Interoperable HIS has a latency of 120 ms, less than the latency of 300 ms used by the Centralized HIS. Also, it offers a higher transaction per second of 2000, because of the ability to surpass the 800 transactions per second by the Centralized HIS. In addition, the Interoperable HIS allows for 5000 users at any one time, which is more than double the 2000 users allowed by the Centralized HIS. These metrics vindicate how the Interoperable HIS is more efficient andscalable than the HIS.

6. Conclusion and Future Works

The proposed research offers a revolutionized model of handling healthcare systems through the development of an integrated health information system – a system that incorporates the use of blockchain technology. This study responds to these three societally important questions related to fragment HIS, data security, and sharing of patient records across facilities. Blockchain, in particular, has brought trust minimization in the form of secure and verifiable exchange of data with no risk of other forms of breaches, tampering, etc. This synthesis guarantees that correct and similar transfers of structures are met across different healthcare platforms enshrined by FHIR/HL7. The proposed hybrid architecture of blockchain network for storing the transaction, cloud storage to store encrypted patient information along with smart contract layer for controlling the access and keep record by its trail is a scalable solution. API middleware handles the exchange of data between the blockchain and the cloud systems as well as the conventional healthcare platforms. Easy to use front end makes it easy for doctors, patient and administrator to access patient records thus improving satisfaction among user. The early tests show that there are 100x faster data access, immutability improved data security, and conformed to required interoperability standards, changing the landscape of patient data and patient care. The given research contributes to the development of the transparent, valuable and secure conditions needed for digital health.
As for future work, future IoT health monitoring-based devices will be installed for capturing data in real time, while the blockchain solution will be expanded on the intersection of Cross border health record sharing, AI and ML techniques will also be applied on a predictive analytics model as part of the healthcare smart world to provide better care for the users in various contexts.

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