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RESEARCH ARTICLE

Engineering Reports

IntelliMedChain: Knowledge Driven and Blockchain Powered Data Sharing Framework for Smart Healthcare

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Abstract

The healthcare profile of an individual is scattered across multiple data sources which can be difficult to access in a timely fashion. Furthermore, while the need to secure an individual's personal health record is of paramount importance to prevent compromises such as cyber-attacks, it is important to be able to be able to seamlessly and quickly share information across healthcare providers to further enable precision and personalized health care. We present IntelliMedChain, a blockchain-powered knowledge-driven data sharing framework that gives patients complete control of their medical data and which can extract rich information hidden in the medical records using knowledge graphs (KGs). By incorporating both blockchain and KGs, we can provide a platform for a secure data sharing amongst stakeholders by maintaining data privacy and integrity through data authentication and robust data integration. We conduct a pilot study of the IntelliMedChain network using Ethereum blockchain technology to share knowledge across stakeholders. We show how it mitigates the issues around scalability by efficiently managing large-scale data and interoperability through seamless adoption of data regulations, as prescribed by various regulatory bodies for efficient governance.

KEYWORDS

Ethereum Technology, Data Sharing, Data Integration, Knowledge Graph

1 | INTRODUCTION

Electronic Health Records (EHRs) [1] were introduced with a broader aim of improving the planning and management of health services [2]. However, more recently, EHRs have been

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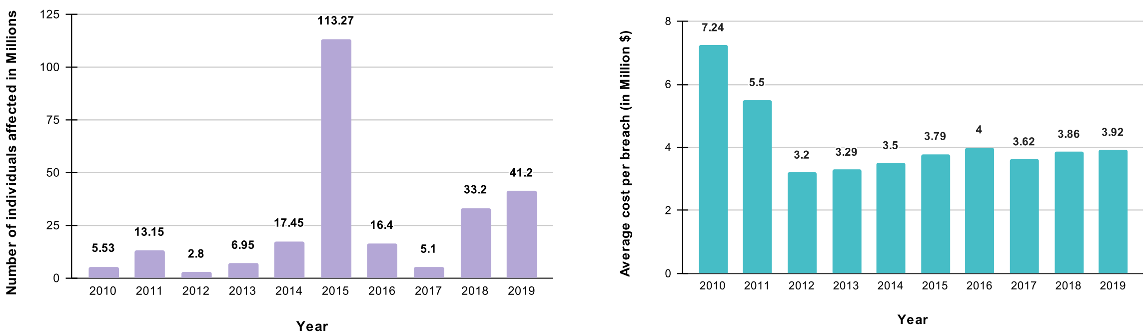
used to increase efficiency in patient diagnosis by accessing the relevant information of the patient's medical history when required, leading to personalised healthcare [3]–[6]. Personalised healthcare is the detailed study of an individual and subsequent treatment that suits the lifestyle, health traits and metabolism of the individual. The data in EHRs ranges from x-rays, laboratory reports, radiology reports to allergies, immunizations, surgeries, medications, family medical history, medical bills, etc. With the introduction of Internet of Things (IoT) and ubiquitous computing, there has been an exponential increase in the seamless integration of Internet-connected devices into our day-to-day lives. According to the European Commission, around 19% of the people in the age group of 19-74 use smart watches and fitness wearables, 11% of the people in the same age group use smart apps that track fitness activities in their daily lives, and 10% of the people use smart devices connected with IoT at home [7]. This ubiquitous integration enables the communication of these devices to track our behaviours, emotions, health, and businesses, covering even minor daily activities to draw hidden insights from them. This leads to the generation of a huge amount of passive data which is rich in intelligence and information in multiple formats ranging from texts, images, videos, sounds, metadata logs, sensor readings, and so on [8], [9]. EHRs, combined with these informative data, have the potential to augment existing diagnostic systems with their intelligent insights [10]. As the data is stored across multiple sources and formats, the seamless integration of these sources and automatic extraction of knowledge from the data is still challenging and new. Moreover, the idea of sharing the personal data even when required brings in two crucial concerns: *privacy* and *security* [11].

1.1 | MOTIVATION

The rapid streaming of voluminous health data from multiple diverse sources has opened the potential to embed vital health stats ranging from cardiac activity, blood pressure monitoring, ECG graphs, monitoring of blood sugar levels, oxygen levels, physical activities, sleep patterns etc. extracted from wearables, sensors, fitness bands etc. which can easily be used to monitor overall fitness status of an individual. Combining these sources with other crucial findings extracted from various media, such as scans, pathology reports, genomic data, clinical and genetic history, allergy conditions, medications for managing diseases and mental health, as well as obtaining vital information can be challenging due to poor data integration strategies. Knowledge Graphs (KG) [12] are a powerful tool that can help to overcome this; a KG can incorporate knowledge from multiple sources and can be a single source of rich information resulting from data integration.



(a) (b)

Figure 1. Statistical analysis of healthcare data breaches: (a) Number of individuals affected per breach; (b) average cost incurred per breach.

There are many instances where personal information has been compromised, sometimes leaked on public sites [13]. According to 2018 Data Breach Investigation Report [14], the

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contribution of healthcare data breaches is the highest among all types of breaches. Figure 1 (a) illustrates the number of individuals affected by data breaches from the year 2010 to 2019 [15]. It can be seen from the graph that the impact was highest in the year 2015, when 113.27 million individuals were affected due to loss of personal health records. There are a number of factors taken into consideration while calculating the financial loss due to data breaches; this includes both direct and indirect expenses incurred by an organisation holding the records. Figure 1 (b) illustrates the average loss per health breach from the year 2010 to 2019, showing that data breaches have an adverse effect both the on privacy of individuals as well as financially on the healthcare industry.

To overcome these issues, we need a secure data sharing framework, which maintains individual ownership of data. The recent advances in cryptographic industry have led to one of the important innovations in the present century, which is to develop a trust-less framework called blockchain. Blockchain [16] is a distributed public ledger that tracks each activity within the system, while encrypting the personal and private information with cryptographic algorithms. A major advantage of blockchain is that it stores each activity on the network in the form of a transaction, thus making it more difficult for malicious users to tamper with the records or for hackers to steal it. While sharing the data across the data sharing system, the interoperability also needs an individual's consent [17] over which portions of the data could be shared. An individual should have the authority to declare the portions of the data that could be shared, before sharing it across the systems.

In this paper, we present a data-sharing framework, IntelliMedChain, to leverage the existing blockchain based EHR systems. One of the finest example of using a data sharing framework with blockchain in healthcare is e-health from Estonia [18]–[20]. Estonia has started working towards e-health since 2008, and it has achieved the latest advancements with decision support systems and continuing towards personalised healthcare across geographical and national borders. The Estonian adoption of a private digital ledger had the goal of using blockchain technology to ensure integrity of health records by tracking medical records of patients. The system was designed to accomplish the following:

1. Efficient large-scale data management without storing any copies of data, performing data authentication without involving third parties;
2. Maintain data integrity and response immediately to any data breaches;
3. Allow interoperability while maintaining data confidentiality and data safeguarding;
4. Real time access to a patient's record, enabling access to vital health information that can be considered during emergency treatment. The system also allows instant viewing of test results and medical images.

With the use of KGs, IntelliMedChain aims to open the potential of shifting the context of such existing healthcare systems towards more patient centric ways to enable personalised healthcare and provide precision medicine in future [21]. Through IntelliMedChain, we attempt to enhance the Estonian blockchain model, the first country in the world to deploy blockchain technology to secure health records as the following:

1. The storage mechanism of medical records and the subsequent updating to the same resulting from patient's encounters;
2. KG as a tool to share relevant portions of data amongst the providers within the healthcare ecosystem;
3. The possibility of the system to make a giant leap towards provision of personalized and quality health care resulting from the vital and current information shared with doctors through the dynamic generation of KG.

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1.2 | CONTRIBUTIONS

This research is an initial proof-of-concept for our perspective article discussing the principles behind such an endeavour [22], [23]. We present IntelliMedChain, a private permissioned data-sharing framework using the Ethereum blockchain technology, to integrate data coming from diverse sources and share data through KGs amongst different stakeholders within the healthcare ecosystem.

The IntelliMedChain data sharing framework aims at following deliverables:

1. Automatic extraction of crucial insights from patients' medical history through KGs obtained through smart contracts;
2. Data sharing platform leading to day-to-day operational ease and hence paving the way for a patient centric approach;
3. Integration of multimodal data distributed across diverse platforms;
4. One-stop-shop solution for enhanced interactions amongst stakeholders in the healthcare ecosystem, while maintaining the data ownership with the patient and guaranteeing privacy and data security during the data sharing transactions.

1.3 | RELATED WORKS

There has been much research using blockchain for sharing data with EHRs [24] and using KGs [25] to extract information from integrated sources. The private [26], [27] and consortium, or federated, blockchains [28], [29] have been proposed in the literature, along with their advantages and features in data integrity. Kim et. al has proposed a framework that shares health data to be used for clinical decisions. The data is extracted and stored in the form of questionnaires and the personal information of an individual is differentiated from the data, ensuring anonymous data to be used for research purposes. Blockchain has been proposed to use for storage and security. Xiao et. al proposed HealthChain [30] using Consortium blockchain, where hospitals, insurance providers and agencies form a consortium. The network is implemented using Hyperledger framework and the complete access remains with the patients. Dubovitskaya et. al proposed Action-EHR, using Hyperledger. The authors propose a EHR sharing framework on blockchain, where the actual data of the patient will be stored on cloud in the form of off-chain storage for scalability while blockchain only contains metadata about the management [31]. Santos et. al [32] proposed Clinical KG, a framework that integrates all the scattered information from biomedical databases, literature, and publications. They propose using the framework with AI/ML algorithms to leverage clinical decision making. Rotmensch et. al [33] present a graph base framework that predicts the diseases that may arise from the given symptoms in Electronic Medical Records data. The framework has been trained upon 270,000 patient visits and evaluated against Google KGs.

1.4 | ORGANISATION

The paper is structured as follows: Section 2 presents a brief overview of our proposed architecture. Section 3 provides a proof of our work with a pilot study carried out with Ethereum as a blockchain platform. In Section 4, we present a discussion around the results of our pilot study, while Section 5 discusses the limitations of our proposed study and future extensions. Finally, Section 6 concludes the chapter.

2 | METHODOLOGY

This section presents the architecture of the proposed framework with its key functionalities and components.

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2.1 | OVERVIEW OF INTELLIMEDCHAIN NETWORK

IntelliMedChain is a decentralised data sharing framework for stakeholders in the healthcare industry powered by blockchain. We aim for ease of interaction amongst all stakeholders of the industry, i.e, patients, doctors, lab technicians, pharmacists, insurance providers, etc. while maintaining privacy of the shared sensitive data. The proposed architecture of IntelliMedChain is depicted in Figure 1.

The patient data is collected using secure data aggregation techniques from diverse sources such as hospitals, healthcare providers, wearables, etc. and processed followed by compression. Data processing is essential in order to bring together all the data together in a standard format. Data compression ensures less storage and faster sharing across the network, while the sensitive data of the patients is secured by encryption using the latest standard cryptographic algorithms [34], [35] such as SHA3-512 [36].

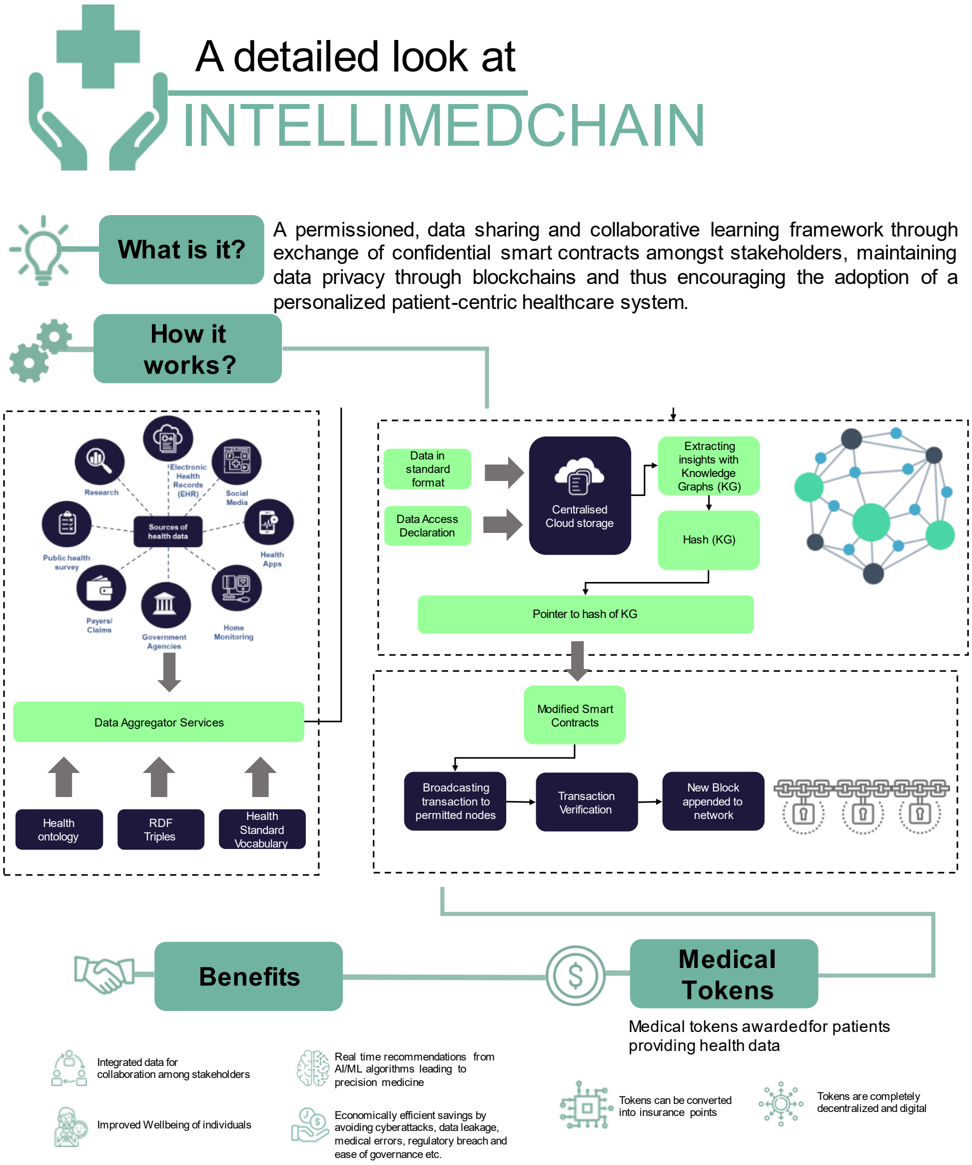

Figure 2. Functionalities of IntelliMedChain network.

The data is typically maintained using a Resource Description Framework (RDF) [37], a standard for data sharing that represents the interconnected data. Each RDF consists of three-

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parts which contain three tuples <subject, predicate, object> describing a resource, each of which is identified by a unique Uniform Resource Identifier (URI). The relations between the resources and the data access permissions for different entities in the healthcare industry are converted into RDF statements following the International Health Standards of HL-7 [38] for subsequent cloud storage. In our system, a resource is a patient and predicate and object are the descriptors of the health data of a patient. This data is then stored into the RDF/cloud storage with predefined access rights from where we integrate and transform the patient data into a KG upon request. For accessing data, different types of permissions are set for different users of the network. The patients at any given time have full rights to grant or revoke access to/from a stakeholder at any instance. The user authentication is validated through smart contracts and verified by all the nodes in the blockchain network.

2.2 | KEY COMPONENTS OF INTELLIMEDCHAIN NETWORK

The key components of the system are discussed in the subsequent sections below.

2.2.1 | RESOURCE-OWNER

A resource-owner in IntelliMedChain is an entity or a person that owns a resource, where resource is the collection of data mapped with an RDF tuple adhering to HL-7 standards. For instance, the RDF tuple for a new-born child to record their birthdate would be: `{fhir:Patient.gender [fhir:value "female"]; fhir:Patient.birthDate [fhir:value "2022-04-28"^^xsd:date;}` [39]. The resource-owner declares the permissions and restrictions about who can access the data. A resource-owner owns a unique address in the blockchain network and interacts with the other stakeholders in the network via blockchain transactions validated through smart contracts.

2.2.2 | REQUESTER

A requester is an entity who requests the resource-owner to access the data for an active session time. These are the stakeholders in the healthcare industry, viz. doctors, surgeons, dentists, pharmacists, lab technicians, insurance providers, etc. If the request owner holds the right to access the data, they request it from the resource-owner, and once resource-owner grants the permission, the requester can access it. The interaction between the resource-owner and the requester is validated and verified through smart contracts.

2.2.3 | BLOCKCHAIN NETWORK

The key mechanism of blockchain to hold all the transactions in the block in a way that every next block holds the address of the previous block, makes is tamper proof. This makes blockchain a viable technology to be used in trust less domains such as such as healthcare.

2.2.4 | WALLET

A wallet is an entity that holds the credentials and details of transactions of a user in a blockchain network. In IntelliMedChain, a wallet holds the user credentials and the transactions between the resource-owner and the stakeholders of the healthcare industry. The wallet also contains all access permissions of the resources defined by the resource owner for the stakeholders.

2.2.5 | TRANSACTIONS

A transaction in blockchain refers to a signed data package that contains a message to send from an externally owned account. The transactions need to follow some rules in order to

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execute or send across the network. In IntelliMedChain, all the healthcare providers will act as the nodes of the network. This process of verifying the transactions is known as mining [16]. There exist several approaches to mine the transactions. The harder the process of mining is, the harder the transactions are to verify. This makes the network more secure as it is complex to tamper the mining process.

IntelliMedChain system consists of following types of transactions on blockchain network:

- *Add patient:* Register a new user on the system by verifying that the patient doesn't already exist in the records. A public and private address will be generated upon successful verification of the user. The public address will then be shared with all users, while the private address will only be be accessible by the patient via the blockchain wallet.
- *Add patient record:* Create new medical records in the IntelliMedChain system that will be stored in the centralised database system. This transaction is accessible to all the stakeholders like patients (to upload their own personal information), doctors, insurance providers, lab technicians (to add medical records for an encounter when a patient visits a hospital). The details of the stakeholder are first verified followed by addition of records into the system.
- *View patient record*: Permit the patient see his/her own medical records. This transaction first verifies the user with his/her public address, ensuring that only the patient's own medical records are accessible by him/her.
- *Request patient data:* Allow stakeholders (patients, insurance providers, pharmacists) other than patient to request the view of the patient data for viewing for some time. The stakeholders can request the data with their public address and then view the data when the patient grants the access to the stakeholders.
- *Generate KG:* Create a KG for specifically requested data. The requester is first authenticated and their access to the data verified. Upon successful verification, the requested data gets extracted from the database, converted to RDF triples and converted to KG.
- *Grant access to the KG:* The requested KG is only shared with stakeholders when the patient grants access to the data. When the patient revokes the access to the data, the data is no longer be accessible the stakeholders, ensuring complete ownership of their data with the patients.

2.2.6 | PUBLIC-PRIVATE KEY PAIRS

Any user in the blockchain network is identified by its unique address in the network. This address is used whenever a user interacts in the network in the form of transactions or while participating in the transaction verification. The addresses are generated in a pair of two: public and private. The public key is published on the network and is accessible to all the users, while the private key is only accessible by the user himself. These key pairs are generated with the help of cryptographic algorithms such as Elliptic Curve Cryptography (ECC).

2.3 | KEY FUNCTIONALITIES OF INTELLIMEDCHAIN NETWORK

This section discusses the key functionalities of IntelliMedChain framework.

2.3.1 | USER CREATION

Figure 3 shows the process of creating users on the IntelliMedChain network. When a new user gets registered in the network, they are given a unique address in the blockchain network by generating a public and private key pair. A cryptographic algorithm such as ECC [40] is used

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to generate these pairs of the addresses. The predefined role from any of the following - patient, doctor, pharmacist, insurance provider, etc. is registered.

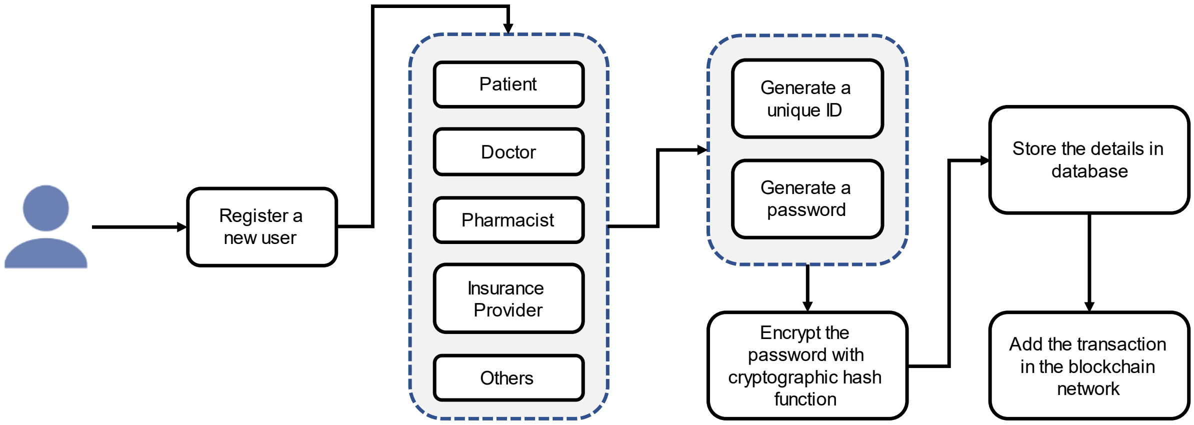

Figure 3. Process of registering a new user on the IntelliMedChain network.

The unique identifiers for users are significant because roles overlap in real-world scenarios, as any user on the network can have multiple roles such as patient, as well as concurrently be a doctor or a pharmacist etc. Once the user is registered on the network, he/she can define the access rights for all the resources owned by him/her.

2.3.2 | DATA AGGREGATION AND KNOWLEDGE REPRESENTATION WITH KG

After a user gets registered on the web-based portal, the data integration component starts collecting all the health data that is linked to the individual. This data is stored on the cloud with the patient's consent. This data can include different EHRs, information from wearables sensors, etc., and can be scattered across diverse sources using different formats. There has been wider research into cryptographically secure data aggregation techniques that plan to reward users for submitting their health information for the centralised database and research. These techniques also take into account automatic user authentication and data validation. This ensures that the user submits the correct information and that the information is only submitted once to maintain data integrity.

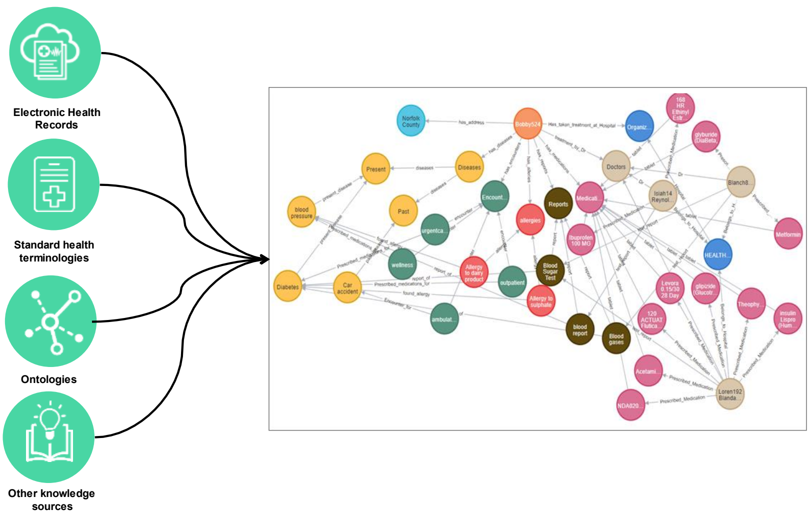

Figure 4. Framework for data integration and their conversion into KG.

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While the data is aggregated, it is also essential to transform the data into an interpretable form that could lead to smart and intelligent interpretations. There are international standards, such as ICD-10 codes [41], defined for healthcare data which helps to extract useful information and discard irrelevant contents. Using these codes, a piece of health information is converted to codes. However, recent research proves that using only such codes is not sufficient as the codes could still miss out on the details of the symptoms and the health conditions. For this purpose, ontologies [42] are used to represent the aggregated information. In IntelliMedChain, ontologies will be the sets of data elements containing the health definitions and their relations with each other. The elements of ontology for health data are obtained from international standards, domain experts, international codes and terminologies for various health conditions, etc. The ontologies are represented in the form of RDF tuples, as RDF adds semantics to the data elements which can be interpreted by humans. For instance, in Figure 4, we can see the process of data aggregation and their conversion into RDF tuples. The RDF tuples and their relationship can be visualised in the form of KGs. The KGs are efficient in terms of speed, interpretability and storage. As we can define relationships using real-world semantics, the KG's can help towards better clinical decisions and judgements.

2.3.3 | ACCESS CONTROL MODEL

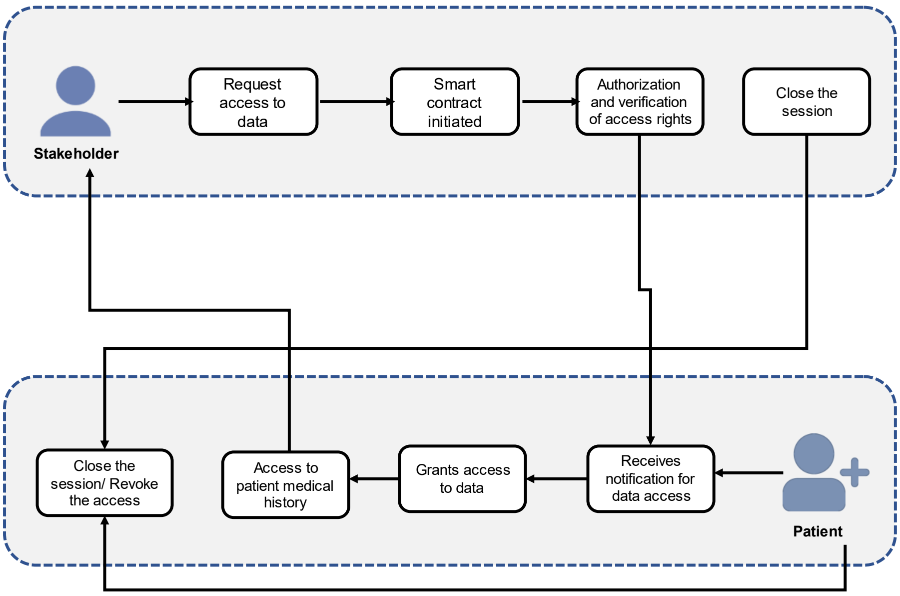

Figure 5. Access Control Model of IntelliMedChain network.

One significant component of the IntelliMedChain system is the access control model, as illustrated by Figure 5. It defines the complete ownership of the data and its access by other stakeholders in the healthcare. The patient can define portions of their health data accessible t different stakeholders over the network, including any or all of their entire historical data on the network. The patient also has the rights to modify the access rights of any stakeholder at any instance of time. This makes the system user-driven, secured and ensures data privacy.

2.3.4 | DATA SHARING THROUGH DYNAMIC KG GENERATION

The data is shared across the network via the KGs which are dynamically created upon the requests of the data. The pipeline in Figure 6 shows the generation of KGs from diverse data sources. When a stakeholder requests data, smart contracts authenticate him/her with the public address on the network and verifies that they have the right to view the requested data. Once

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the data owner (patient) approves the request to view the data, the requested data is then aggregated and converted to RDF tuples in accordance with standard prescribed formats in FHIR. The KGs gets generated from the data and shared across the stakeholders and the tuples are linked with ontologies to develop a relation with them. The tuples form the nodes of the KGs while the ontologies form the edges. We propose to predefine the importance of various encounters of patients in consultation with the stakeholders of the ecosystem to determine the addition of the related KG to the database. If the importance is considered low, we discard the KG, while a higher-importance encounter will result in the KG being appended as a new record into the patient's existing EHR. The transactions are then verified within the peer-to-peer network of blockchain with a Proof-of-Work consensus algorithm [43] deployed in the network and appended to the blockchain. We don't store any KG's using blockchain, as they are dynamically created during the session. However, we update the data integration with the encounter details depending upon the importance of the event. The advantage of performing all data sharing activities through blockchain is the mitigation of risk of highly sensitive data becoming compromised by some malicious actor Blockchains record timestamps of each instance of access or modification performed on the patient records. Its cryptographic hash functions make it possible to trace and monitor all activities.

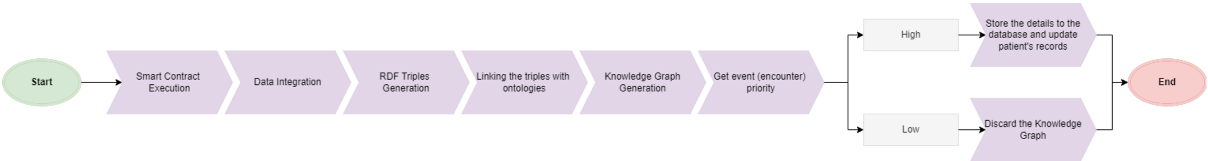

Figure 6. Pipeline of data sharing with KG generation.

3 | PROOF OF CONCEPT OF INTELLIMEDCHAIN WITH ETHEREUM

In this section, we present a pilot study of our proposed IntelliMedChain network and discuss the dataset used for experimentation, network setup and potential use cases for the network.

3.1 | DATASET DETAILS

For IntelliMedChain pilot testing, we have used the samples of synthetic health records generated with open-source software Synthea [44]. The dataset consists of 14 different files of data covering healthcare transactions in the healthcare industry for synthetic patients. The 10 most common encounters in the healthcare industry with 10 highest morbidity chronic conditions have been provided in the dataset. The data is based on the statistics of the United States and also adheres to universal healthcare standards [45, 46] such as Health Level – 7 (HL7) and, in multiple formats like csv, FHIR, C-CDA. The data of 1000 sample patients in csv format were used for the IntelliMedChain network testing.

3.2 | EXPERIMENTAL SETUP AND EMPIRICAL ANALYSIS

This section presents the experimental setup with a private Ethereum blockchain network setup by the authors.

3.2.1 | PRIVATE BLOCKCHAIN NETWORK

We set up a private 7 remotes node Ethereum network with the configurations as:

{*Node 1*: 8 GB RAM, 1.19 GHz, *Node 2*: 4 GB RAM, 1.80 GHz, *Node 3*: 8 GB RAM, 1.19 GHz, *Node 4*: 8 GB RAM, 2.5 GHz, *Node 5*: 8 GB RAM, 2.4 GHz, *Node 6*: 12 GB RAM, 2.20 GHz, *Node 7*: 16 GB RAM, 2.20 GHZ}

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The root node that defines the mining rights to other nodes was at Node 1, and each of Node 2, Node 3 and Node 4 were given rights to mine the transactions. Nodes 5 through 7 were not given permission for mining. This setup was to accurately model a blockchain network in which all nodes do not have the same mining permissions. The blockchain private network was built using geth and Puppeth tool and Web3j library for smart contracts. Geth (Go Ethereum) [47] is a command-line client interface tool that allows users to create and interact with private Ethereum blockchains. Puppeth [48] is a CLI tool that helps generate genesis blocks, which are initialization files for the nodes to get registered on the network. Web3j [49] is a library used to invoke smart contracts. All the remote nodes were connected in a network using a virtual private network. After connecting nodes, to test and verify the connection between them, we start mining on the first node and verify that the changes are reflected on the other nodes. In the proposed system, all the participating hospitals will be the nodes, and doctors, patients, and pharmacists will be the users. The users will interact with each other using smart contracts.

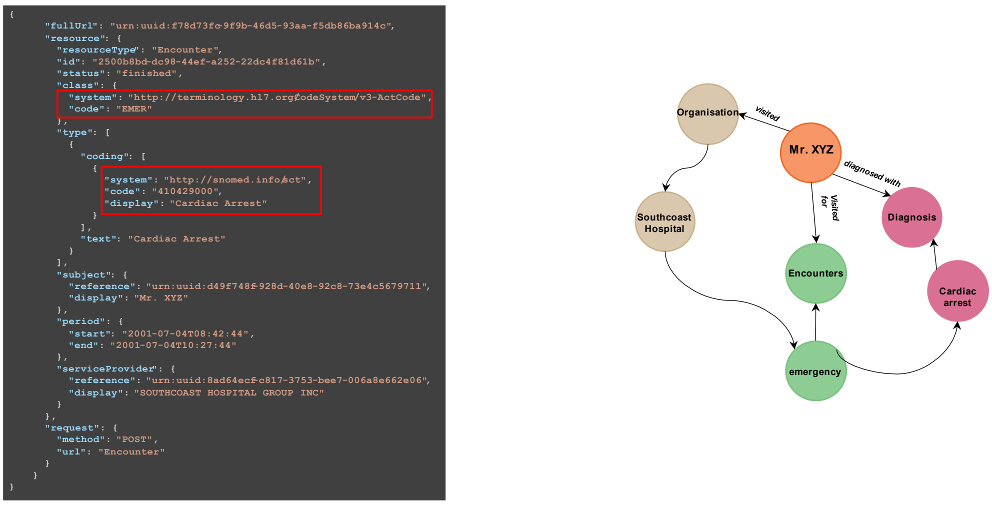
3.2.2 | DATA INTEGRATION AND KNOWLEDGE GRAPH GENERATION

We tested our proposed framework on the dataset using our private blockchain network. To illustrate how data sharing works, let us consider a scenario when a doctor requests a portion of the data for a patient when he visited the hospital last time. For this scenario, we have used a sample of a patient from the dataset where the patients visit the hospital for an encounter of cardiac arrest. The details for his encounter are shown in Table 1.

Table 1. Details of an encounter of a sample patient from the dataset.

Encounter ID	2500b8bd-dc98-44ef-a252-22dc4f81d61b
Patient ID	d49f748f-928d-40e8-92c8-73e4c5679711
Organisation ID	23834663-ed53-3da9-b330-d6e1ecb8428e
Encounter Class	emergency
Description	Cardiac Arrest
Start date	2001-07-04T08:42:44
End Date	2001-07-04T10:27:44

When the doctor requests the data, a smart contract would get initiated and will verify the authentication of the doctor with his public address, along with his authorisation to view the data.



(a) (b)

Figure 7. Demonstration of KG generation pipeline: (a) conversion of aggregated data into RDF tuples; (b) generation of KG from RDF tuples and ontologies.

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After successful verification, the data would then be converted to RDF triples using the FHIR standard as illustrated in Figure 7 (a). The highlighted sections of the triples illustrate an example of conversion of the details to prescribed codes. From Table 1, the encounter class **emergency** is converted to **EMER** according to FHIR while the description for **cardiac arrest** is converted to **SNOMED code 410429000**. These RDF triples are generated from the nodes of the KG, while the ontologies are used to develop a logical relation between them. In this pilot study, we have pre-defined the ontologies for the dataset, although the automatic generation of ontologies will be in future work. The KG generated from these triples is as illustrated in Figure 7 (b).

3.2.3 | COMPUTATIONAL COSTS OF TRANSACTIONS ON INTELLIMEDCHAIN

We also tested the scalability of the proposed framework in terms of computational efforts. The computational cost to verify the transactions are paid by the user who requests the transaction verification, in the form of transaction fees [50] as calculated using Equation (1).

$$transaction\ fees = total\ gas\ used * gas\ price \quad (1)$$

Here, gas measures the computational efforts required to execute any operations on the Ethereum blockchain network and is measured in the units gwei, where 1 gwei is around \$0.00000255 as of 6th May 2022.

The transaction fees are dependent on multiple factors, such as the complexity of the smart contracts, the gas price paid and the frequency of smart contracts used in the transactions. Ethereum has its own cryptocurrency, ether, with a single ether currently worth approximately \$2,734 as of 6th May 2022 [51]. One significant factor impacting transaction fees is the gas limit on transaction costs. The *gas limit* determines the maximum gas price a block can have and the number of transactions that a block can contain.

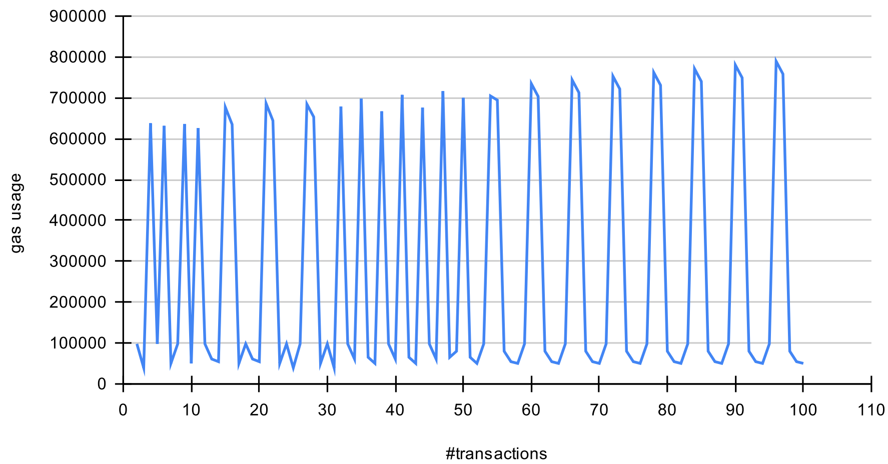

Figure 8. Transaction cost analysis in the form of gas usage for IntelliMedChain. The data sharing transactions requires more gas usage as it involves multiple processes to authenticate and authorise the user, and share the data for the active session. Hence, we observe a spike in the graphs for such transactions.

In our pilot study, we calculated the cost of transactions on public network of ganache-cli [52] for a batch of 100 transactions, where the costs of transactions are shown in Figure 8. The parameters while performing the transactions were: {*gasLimit*: 6721975, *gasPrice*: 20 gwei}.

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We performed 100 transactions over IntelliMedChain network and calculated the transactions costs to verify the transactions in the network. The transactions performed were among the ones mentioned in Section 2.2.5. The average gas usage for 100 transactions was 276940.5941 gwei, which is equivalent to 0.1344395 Ethers or $373.57 (as of 6th May 2022). The transactions where data is shared require more than one authentication process to verify whether the entities are legitimate, hence, these transactions require more gas usage compared to others. This analysis gives an idea about identifying the impact of various factors on transaction costs while planning a business model.

While converting the proposed system to a business model, we propose the following incentive mechanism for IntelliMedChain:

- *Generation of quality data:* Patient data is generated from multiple sources in multiple formats. The data can be validated using algorithms such as information entropy to verify whether they meet the standard data formats. If the data provided by the patients meet the guidelines, the patients can be incentivised in the forms of corresponding credits which can be redeemed by cash or coupons for medical services. One such instance of using health tokens is Medcoin from MedChain [53]. MedChain is a blockchain based EHR system in practise in USA and uses medcoins as tokens. The tokens are used to upload the data on servers and mining cycles payment.
- *Optimal retrieval of data:* Data requests by stakeholders in the network is evaluated for performance on the basis of time of retrieval and confirmation of transactions on the network. Nodes can be rewarded on the basis of the time and efficiency of retrieval.

4 | USE CASES FOR INTELLIMEDCHAIN

This section discusses the use cases of the proposed network.

4.1 | DATA INTEGRATION FROM DIFFERENT MODALITIES LEADING TO A DATA SHARING FRAMEWORK

Whenever a communication is requested between two stakeholders of IntelliMedChain, a smart contract gets initiated. We illustrate in Figure 9 three different scenarios, such as, patient-doctor interaction, patient-pharmacist interaction and patient-insurance provider for establishing communication amongst different stakeholders. These scenarios are depicted from a sample patient details from the dataset. The smart contract will automatically extract the accessible portions from the data according to the role of the requester, at which point it will generate a KG from the data. For example, while a doctor may have access to the entire historical data, such as past/current diseases of the patient, a pharmacist's KG will likely only include medications prescribed to the patient, the name of the doctor who prescribed them, and the date of diagnosis, recommended dosage etc. On the other hand, an insurance provider will have access to contents required for filling in the claim's benefits.

4.2 | PERSONALISED RECOMMENDATIONS FROM THE CRUCIAL INSIGHTS OBTAINED THROUGH INFORMATION RICH KG

The information-rich customised KG's holds the potential to disrupt future health care ecosystems by shifting towards personalised healthcare tailored according to each individual leading to improved health, less burden on the staff and a crucial step towards precision medicine. For example, Figure 10 shows a detailed KG extracted from the dataset for a sample patient, with nodes and their relationships between them.

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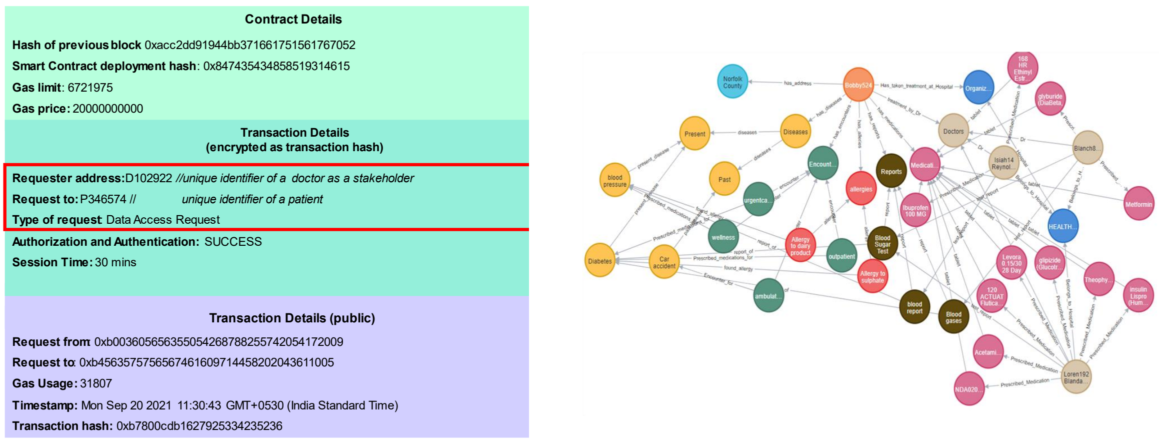
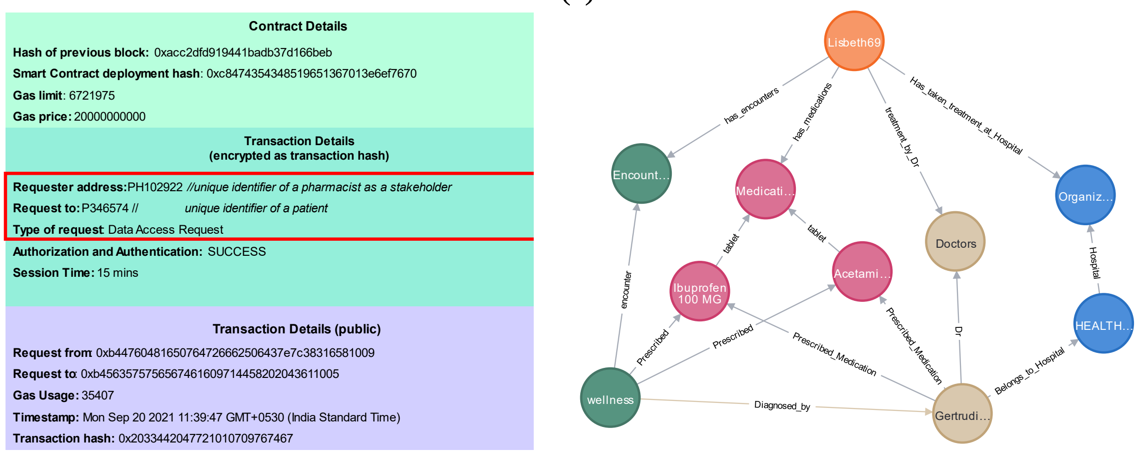
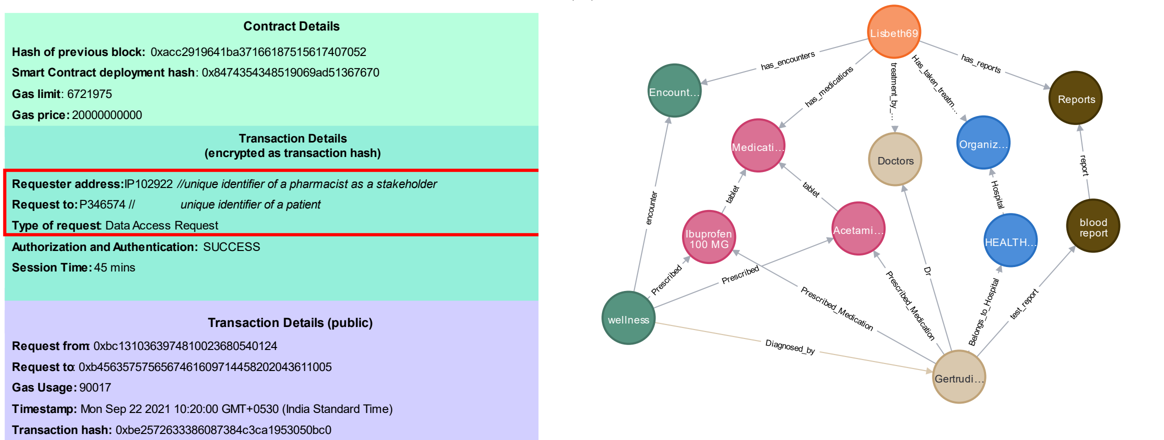


(a)



(b)



(c)

Figure 9. Smart contracts to initiate data sharing among a single patient and three different stakeholders in the IntelliMedChain network. The KGs are generated using patient detail from the dataset. The adjacent KG shows the knowledge sharing when the stakeholders request the data; (a) contains a smart contract for a doctor and a patient transaction; (b) shows a smart contract and knowledge sharing for a pharmacist and a patient; (c) presents a smart contract and knowledge sharing for a insurance provider and a patient. The knowledge shared differs according to the predefined rights of the stakeholders to access the relevant portions of the data and the data requested at the time of transaction. Here, green nodes represent encounters, red nodes represent allergies, pink nodes represent diseases, brown nodes represent medications and wellness.

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The different coloured nodes represent different entities for a patient which, when accumulated together, holds the promise to deliver crucial intelligent insights. As seen in Figure 9, green nodes represent encounters, red nodes represent allergies, pink nodes represent diseases, brown nodes represent medications and wellness. Such a graph can reveal vital statistics about a patient suffering from chronic blood pressure, diabetes and allergic to sulphates. The doctor can also view all the medications that were prescribed to the patient and if the medication is still active. This rich information will help a doctor to advise, taking into account all these factors in the next visit of the patient.

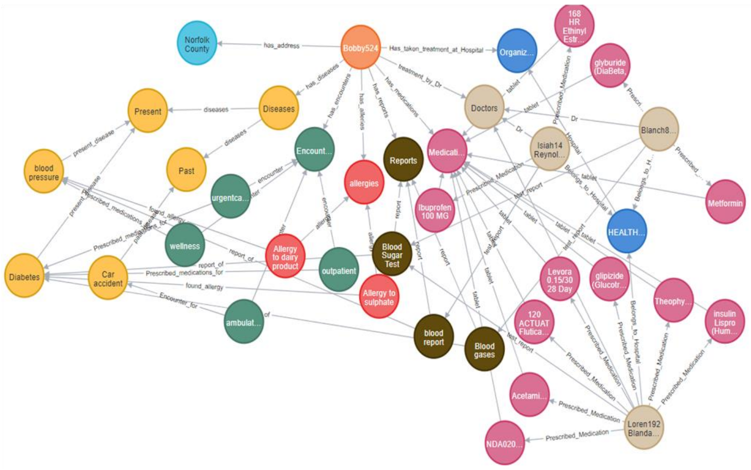

Figure 10. A sample KG revealing critical insights about a patient. As above, green nodes represent encounters, red nodes represent allergies, pink nodes represent diseases, brown nodes represent medications and wellness. The KG is generated from a patient's details from the database.

4.3 | MAINTAINING DATA INTEGRITY THROUGH BLOCKCHAIN

Blockchain has the unique characteristic of tracing, which enables it to identify malicious activity on the network. This ensures that if a malicious user tries to tamper with the KG, the pointer has to be accessed from the blockchain, and hence the account can be traceable as illustrated in Figure 11.

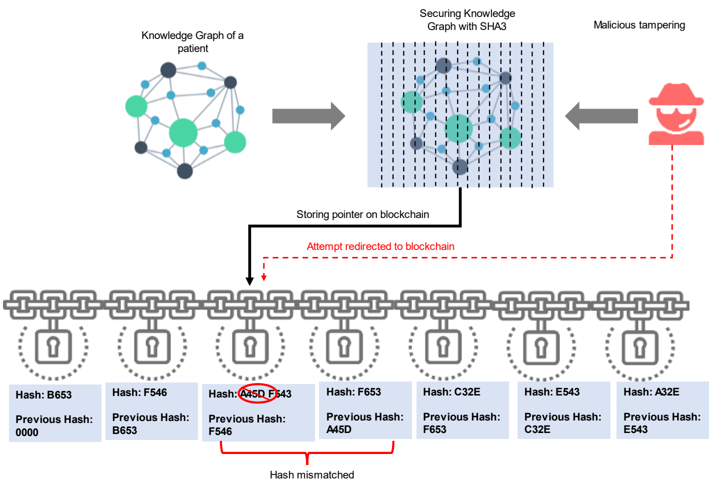

Figure 11. Example of data tampering prevention in IntelliMedChain blockchain network.

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For example, if a malicious user wants to change the contents of the Block 3 in Figure 11, the hash of Block 3 will change. As the hash of the block is always the hash of the current blocks and the hash of the previous blocks, all the blocks after block 3 will change, and thus the attack can easily be located.

5 | CONCLUSIONS AND FUTURE WORK

In this research, we demonstrated a novel EHR data-sharing framework using a blockchain network. Our proposed framework, IntelliMedChain, includes three key aspects: first, compared with traditional data integration solutions, our approach adopted cutting-edge semantic technologies to manage the complexity of massive data sharing transactions. Second, with the help of advanced blockchain techniques, our framework offers data protection during multiple data sharing transactions. Finally, our approach also has a sophisticated and flexible web-based interface that can synchronously work with the proposed data-sharing framework.

Through these benefits the proposed framework can tackle the core concerns of current smart healthcare applications and provide the stakeholders a simple, secure and convenient data-sharing platform. In future work, we plan to run pilot tests with different hospitals, and hence improve the framework based on the feedback of users. The application of our framework can help users to share the sensitive data in these healthcare domains securely and achieve a much better and comprehensive understanding of the complicated scenarios which can lead to reduced medical errors and thus potentially save lives.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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