Decentralized Management of Medical Test Results Utilizing Blockchain, Smart Contracts, and NFTs

Quy T. L.[1], Khanh H. V.*[1], Huong H. L.[1], Khiem H. G.[1], Phuc T. N.[1], Ngan N. T. K.[2], Triet M. N.[1], Bang L. K.[1], Trong D. P. N.[1], Hieu M. D.[1], Bao Q. T.[1], and Khoa D. T.[1]

[1]FPT University, Can Tho City, Vietnam
[2]FPT Polytechnic, Can Tho city, Vietnam

***Abstract*— In today's medical landscape, the effective management and availability of diagnostic data, including current and historical medical tests, play a critical role in informing physicians' therapeutic decisions. However, the conventional centralized storage system presents a significant impediment, particularly when patients switch healthcare providers. Given the sensitive nature of medical data, retrieving this information from a different healthcare facility can be fraught with challenges. While decentralized storage models using blockchain and smart contracts have been suggested as potential solutions, these methodologies often expose sensitive personal information due to the inherently open nature of data on the blockchain. Addressing these challenges, we present an innovative approach integrating Non-Fungible Tokens (NFTs) to facilitate the creation and sharing of medical document sets based on test results within a medical environment. This novel approach effectively balances data accessibility and security, introducing four key contributions: (a) We introduce a mechanism for sharing medical test results while preserving data privacy. (b) We offer a model for generating certified, NFT-based document sets that encapsulate these results. (c) We provide a proof-of-concept reflecting the proposed model's functionality and (d) We deploy this proof-of-concept across four EVM-supported platforms—BNB Smart Chain, Fantom, Polygon, and Celo—to identify the most compatible platform for our proposed model. Our work underscores the potential of blockchain, smart contracts, and NFTs to revolutionize medical data management, demonstrating a practical solution to the challenges posed by centralized storage systems.**

***Keywords*—Medical test result; blockchain; smart contract; NFT; Ethereum; Fantom; Polygon; Binance Smart Chain**

I. Introduction

Advancements in technology are significantly transforming the landscape of disease diagnosis and treatment, alleviating the need for patients to physically visit healthcare facilities. Innovative applications installed on smartphones now enable remote health monitoring, overseen by either human doctors or AI platforms [1]. However, to supplant the entire traditional healthcare system, certain critical steps outlined in numerous research directions must be taken [2], [3], [4]. One significant challenge is the management of individual medical data, including treatment records and medical history. Accurate recording of medical history is vital for effective disease diagnosis and treatment [5].

Many research studies leverage modern technologies to reform healthcare systems, replacing traditional supply chain processes [6], [7], and the way diseases are diagnosed and treated. These proposed solutions primarily focus on decentralized (or distributed) storage, ensuring efficient data handling and access [8]. Blockchain technology and smart contracts contribute to transparency in information storage [9]. After authentication, all data is stored on-chain and becomes immutable.

Smart contract technology, introduced first by the Ethereum platform[1], automates all system operations. After calculations and updates, information and data are stored on a distributed ledger, accessible for stakeholders to check activities.

Blockchain-based solutions have been proposed to ensure data authentication transparency in the medical environment, addressing shipping [10], [7], disease treatment [11], [12], medical waste management [13], emergency patient information retrieval [14], [15], medical product supply chain [16], and blood donation processes and their supply chain management [17], [18]. Other non-medical solutions based on community sourcing include Cash on Delivery [19], [20], supply chain [21], [22], among others [6], [23].

Several models for managing patients' medical examination and treatment information based on Blockchain technology have been proposed. For instance, HealthBank[2] introduced a patient information management model based on Blockchain technology, where users can store all information reliably on the blockchain. Similarly, HealthNautica and Factom Announce Partnership[3] utilized the transparency of on-chain storage to build a system protecting medical data integrity.

However, on-chain storage of all patient information encounters two significant issues: i) a decrease in system performance and increased transaction fees per access; ii) lack of patient privacy due to public access to all information. The first problem arises from redundant and unnecessary data storage [24]. Thanh et al. [20] posited that not all collected data needs to be stored and processed on-chain as most are redundant. Trieu et al. [14] shared a similar sentiment, suggesting off-chain storage for personal data unrelated to treatment or diagnosis. This decrease in on-chain data consequently reduces transaction costs [25].

Privacy risk is another issue; unencrypted stored data can be exploited and manipulated by other system users, severely

[1]https://ethereum.org/en/whitepaper/
[2]https://www.healthbank.coop
[3]https://www.factom.com/company-updates/healthnautica-factom-announce-partnership/

impacting patient privacy. Insurance companies, for example, can misuse a patient's medical history, refusing to provide coverage [26]. To address this, some Blockchain and IPFS-based solutions, such as Misbhauddin et al. [27] and Zyskind et al. [28], store sensitive user data off-chain (in IPFS), minimizing personal information exposure risk.

Still, these solutions struggle with medical record sharing between patients and medical centers (i.e., medical staff). To address this, we propose an approach based on Blockchain, smart contract, and NFT technologies. Here, personal information and treatment history are stored as NFTs, and medical test result-related information is stored off-chain. NFTs are generated for each test and shared easily with required addresses (e.g., nurses, doctors). Each patient is assigned a unique identifier to differentiate them from others.

Our work thus provides four key contributions: (a) A Blockchain, smart contract, and NFT-based mechanism for sharing test results. (b) A storage model based on the NFT tool. (c) A proof-of-concept implemented based on the proposed model. and (d) Deployment of the proof-of-concept on four platforms that support ERC721 (NFT of ETH) and EVM (for deploying smart contracts written in solidity language) including BNB Smart Chain, Fantom, Polygon, and Celo to determine the most suitable platform for our proposed model.[4]

The structure of this paper unfolds over eight sections. Following the introductory part, we provide background information, offering an overview of contemporary studies addressing similar research issues and a summary of relevant technologies and EVM-compatible blockchain platforms in Section II. In Section III we explore related work. The subsequent two sections delve into our methodology and the practical implementation of our proposed model (refer to Sections IV, V). To attest to the efficacy of our approach, Section VI presents an evaluation conducted under various scenarios, preceding the discussion in Section VII. Finally, in Section VIII, we provide a summary and outline future directions for this research.

II. BACKGROUND

This section provides a detailed background to the technologies central to the decentralized management of medical test results. Specifically, we explore Blockchain, Smart Contract, Non-Fungible Tokens (NFTs), Ethereum, Binance Smart Chain, Polygon, Celo, and Fantom. Due to the limited scope of this paper, we cannot provide the details on each topic. We prefer the reader follow the white paper/external source if they want to detail the corresponding platforms or topics.

A. Blockchain

Blockchain technology forms the backbone of many decentralized systems, including cryptocurrencies like Bitcoin. It employs a distributed ledger, functioning as a shared database spread across multiple nodes in a network. Each block in the chain contains data, and every new block is linked to the preceding block, forming a chain-like structure. It is the Blockchain's immutable and transparent nature that makes it attractive for various applications, including medical data management.

[4]We did not deploy smart contracts on ETH due to the high execution fees of smart contracts.

B. Smart Contract

Smart contracts are self-executing contracts with the terms of the agreement directly written into lines of code. They eliminate the need for a middleman in digital agreements, ensuring trust, transparency, and efficiency. Smart contracts execute automatically upon meeting predefined rules and conditions. They are stored on the blockchain, making them tamper-proof and traceable. These features make smart contracts a valuable tool in healthcare, specifically in managing and securing patient data.

C. Non-Fungible Tokens (NFTs)

NFTs represent a unique digital asset that is verifiably unique, unlike cryptocurrencies such as Bitcoin or Ethereum, where each unit or "coin" is identical to every other coin. This uniqueness and indivisibility make NFTs ideal for representing ownership or proof of authenticity of individual items or assets, such as artwork, real estate, and in our context, unique sets of medical test results.

D. Ethereum

Ethereum is an open-source blockchain platform that supports smart contract functionality. It provides the underlying technology for a multitude of decentralized applications (DApps). Ethereum also introduced the concept of programmable transactions using smart contracts, making it a pioneer platform for building complex decentralized applications, including those for decentralized healthcare systems.

E. Binance Smart Chain (BSC)

The Binance Smart Chain[5], an innovation by the Binance cryptocurrency exchange, is a blockchain platform built for running smart contract-based applications. It allows developers to build decentralized applications efficiently and is fully compatible with Ethereum Virtual Machine (EVM). BSC also boasts high transaction speed and low fees, making it a favored platform for various decentralized projects.

F. Polygon

Polygon or MATIC [6], previously known as Matic Network, is a layer-2 scaling solution for Ethereum. It aims to provide faster and cheaper transactions on the Ethereum blockchain while maintaining its robust security. Polygon uses a technology known as 'sidechains,' which are blockchain systems that run alongside the Ethereum mainchain. This feature allows for scalability, making it suitable for a decentralized medical test result management system.

G. Celo

Celo[7] is an open blockchain platform that makes financial tools accessible to anyone with a mobile phone. It's designed to support stablecoins and tokenized assets, prioritizing scalability, and usability. Celo's lightweight identity and proof-of-stake mechanisms make it an attractive platform for projects needing secure, fast, and low-cost operations, such as those required in managing medical test results.

[5]https://github.com/bnb-chain/whitepaper/blob/master/WHITEPAPER.md
[6]https://polygon.technology/lightpaper-polygon.pdf
[7]https://celo.org/papers/whitepaper

H. Fantom

Fantom[8] is a high-performance, scalable, and secure smart-contract platform. It is designed to overcome the limitations of previous generation blockchain platforms. Fantom is permissionless, decentralized, and open-source. Its aBFT consensus protocol delivers unparalleled speed, security, and reliability. Fantom's technology stands out for its speed, low transaction costs, and high security, making it a good option for any decentralized application like managing medical test results.

III. Related Work

This section critically surveys the past methodologies employed in creating models for patient test results management, particularly those harnessing Blockchain technology and smart contracts. The study is bifurcated into two core perspectives: i) patient-centric health information management models, and ii) strategies based on blockchain technology.

A. Patient-Oriented Health Information Management Models

In the rapidly evolving healthcare landscape, the patient-centric model has emerged as a pioneering approach, prioritizing patients' needs and values. The key aspect of these models is to cater to patients' privacy preferences, providing them with the ability to have greater control over their health data. The type of data that falls under this model not only includes clinical details essential for disease management and treatment like heart rate, blood pressure, and other vital health indicators, but also personal data like location, phone number, and more. While not all data are directly relevant for treatment, they are critical components of comprehensive patient care.

Among the remarkable contributions in this space is a model introduced by Chen et al. [29]. This innovative approach utilizes Internet of Things (IoT) devices and sensor technology, which are embedded directly into patients. The devices are leveraged to extract vital medical information in real-time. In this model, blockchain technology plays a pivotal role in securely storing, managing, and controlling the harvested data from these IoT devices. The collected information is encrypted before leaving the patient's control and is sent directly to cloud servers.

An intriguing shift away from conventional models is observed in these novel approaches. Traditional models entrust medical centers or hospitals with the storage and management of patient information. In contrast, the newer methodologies propose a paradigm shift, advocating for the patients' power to control their data [30], [31], [32]. This is essentially empowering patients to decide who they want to share their data with, ensuring that data sharing occurs only with trusted entities.

Further substantiating the value of patient empowerment, Makubalo et al. [33] collated several models that endorse health information sharing by patients themselves. In order to prevent the illicit sharing of information by those it has been shared with (like doctors or nurses), a robust system was introduced by Yin et al. [34]. This system employs attribute-based encryption (ABE) to secure data privacy, providing patients the ability to define their data access policies.

[8]https://whitepaper.io/document/438/fantom-whitepaper

This shift towards patient-centered models has fostered a diverse body of work in the area of health data management and privacy. Several other studies have adopted ABE-based access control models, and dynamic policy models to enhance flexibility in the healthcare environment [35], [36], [24]. All these advances reflect the broader move toward empowering patients and improving the flexibility and privacy of health data management.

B. Blockchain-based Health Information Management Models

A distinct, parallel body of research focuses on the implementation of blockchain technology in healthcare data management. In these models, the emphasis is on i) the development of a decentralized management system for patient medical data, inclusive of laboratory information, and ii) the utilization of the InterPlanetary File System (IPFS) for reducing the volume of on-chain stored information.

Madine et al. [37], for instance, proposed a model that stored medical records on a blockchain, preserving the detailed information on IPFS. This approach seeks to achieve a delicate balance between information accessibility and privacy, with a clear objective of safeguarding patient data against unauthorized access from within the same system.

In a similar vein, HealthBank and HealthNautica introduced blockchain and IPFS amalgamations to propose patient-centric models complying with privacy regulations, like the General Data Protection Regulation (GDPR). These models promote the concept of decentralization in healthcare, eliminating the reliance on a central authority for data storage and management, and significantly enhancing data security.

Noteworthy is the evolution of these models beyond simple storage to include sharing of essential information with authorized individuals, such as medical staff at healthcare centers [38], [39]. This represents a more comprehensive approach to health data management, incorporating the need for data sharing in addition to secure storage.

Another pertinent aspect addressed by some studies is the consideration of indirect participants in the treatment process, such as insurance companies and regulators [40]. This approach is especially important as it encompasses the complete ecosystem of healthcare, from patient care to insurance processes and regulatory compliance.

Despite these advances, the field faces a host of challenges. For example, the user-centric model often results in policy redundancy, and the introduction of new blockchain and IPFS-based systems can be complex for users unfamiliar with such technologies.

To circumvent these challenges, our proposed model incorporates a fusion of modern platforms, including blockchain, smart contracts, and Non-Fungible Tokens (NFTs). Rather than depending on sharing policies to define access to test results or patient history, we propose the creation of corresponding NFTs. This approach is designed to alleviate stringent platform requirements, such as those associated with security policy-based methods. The following section elucidates our proposed model that employs NFT technology (i.e., ERC721) to share information with the appropriate entities.

IV. Blockchain-Facilitated Medical Test Results Management Framework

In the ensuing discussions, we will initially revisit the traditional methodologies employed in medical test results management. Following this, we introduce our novel model, which is underpinned by Blockchain technology, smart contracts, and Non-Fungible Tokens (NFTs).

A. Conventional Model for Managing Medical Test Results

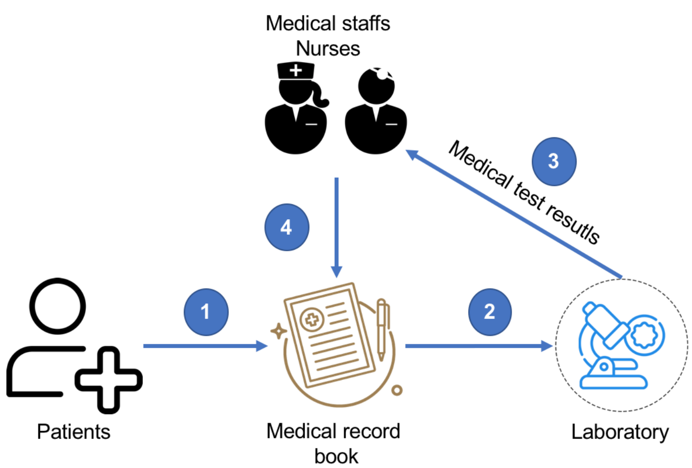


Fig. 1. Conventional medical test results management framework.

Fig. 1 illustrates the conventional procedure for testing and obtaining results, typically structured around four key stages. A patient, in the initial stage, constructs a medical record book, either in electronic or physical form, at the medical institution. This repository houses comprehensive information pertinent to the patient's treatment process and medical test results.

These records are absolutely critical, as the clinicians' diagnostic decisions and medical judgments hinge on the variations observed in a patient's health status as interpreted from these test results. In many developing nations, the testing phase could be quite protracted due to constraints related to infrastructure and auxiliary medical equipment. The patient, consequently, has to endure substantial waiting periods to provide samples and receive the corresponding test results.

Upon receipt of the results from the laboratory personnel, the patient presents these results to the medical practitioners for an assessment of their health status and determining the appropriate therapeutic interventions. All data concerning the diagnosis and resultant treatment are updated in the medical record book.

The loss of a patient's medical record book, thus, severely jeopardizes the treatment process. For the digital variants, the medical record book is stored locally at a discrete hospital or healthcare facility. Given the highly sensitive nature of medical data, the prospects of sharing this information with other institutions are typically slim. Therefore, there exists a pressing need for a comprehensive solution to issues related to the storage and sharing of patients' medical record books, catering to both electronic and physical formats. In the subsequent segment, we unveil our resolution, leveraging the capabilities of contemporary technologies like blockchain, smart contracts, and NFTs.

B. Medical Test Results Management Model Leveraging Blockchain Technology, Smart Contracts, and NFTs

Fig. 2 exhibits our solution, drawing upon blockchain technology, smart contracts, and NFTs, and comprising of nine critical stages. Users are provided with the ability to create an identifier, referred to as 'patient_ID_global,' which is valid across all medical systems (step 1). This identifier is further linked to a medical record book that archives all relevant details about the medical record, test results, and the patient's medical history (step 2). Steps 3-6 are intrinsically connected with User-Interface (UI) services, offering interfaces to every user group within the system to curtail complex operations (i.e., backend processing). These interactions are facilitated via smart contracts housing pertinent functions for data storage and processing (step 7). In this phase, we devise functions relating to contract creation/NFT or the transfer of NFTs (refer to the introduction).

All transactions are subsequently updated, stored, and dispersed within a distributed ledger, including details about visitors, time, and location, etc. The information relevant to the test results is produced in the corresponding NFTs and transferred to the physicians responsible for treating the patient (step 9).

V. Implementation

The practical application of our model zeroes in on two primary objectives: i) manipulation of data, specifically medical test results, involving creation, query, and update on the blockchain platform, and ii) construction of Non-Fungible Tokens (NFTs) for medical test results, enabling the easy sharing of such data by patients with medical practitioners such as doctors and nurses.

A. Data Creation Procedure

Fig. 3 provides a graphic representation of the steps involved in data initialization with respect to the medical test results. These results incorporate information such as the type of test conducted, time of testing, testing facility, test results, consultation outcomes, and the corresponding treatment approach and its duration. Additionally, metadata of the test results also includes information about the type of patient and the medical personnel involved in conducting the test.

The storage process, in this context, facilitates concurrent storage (i.e., distributed processing as a peer-to-peer network) on a distributed ledger, which supports multiple users for concurrent storage, thereby reducing system latency.

In essence, the medical test results data is structured as follows:

```
medicalTestResultsObject = {
"patientID": patientID,
"medicalTestID": medicalTestID,
"medicalStaffID": medicalStaffID,
"type": type of test,
"numbers": numbers of treatments,
```

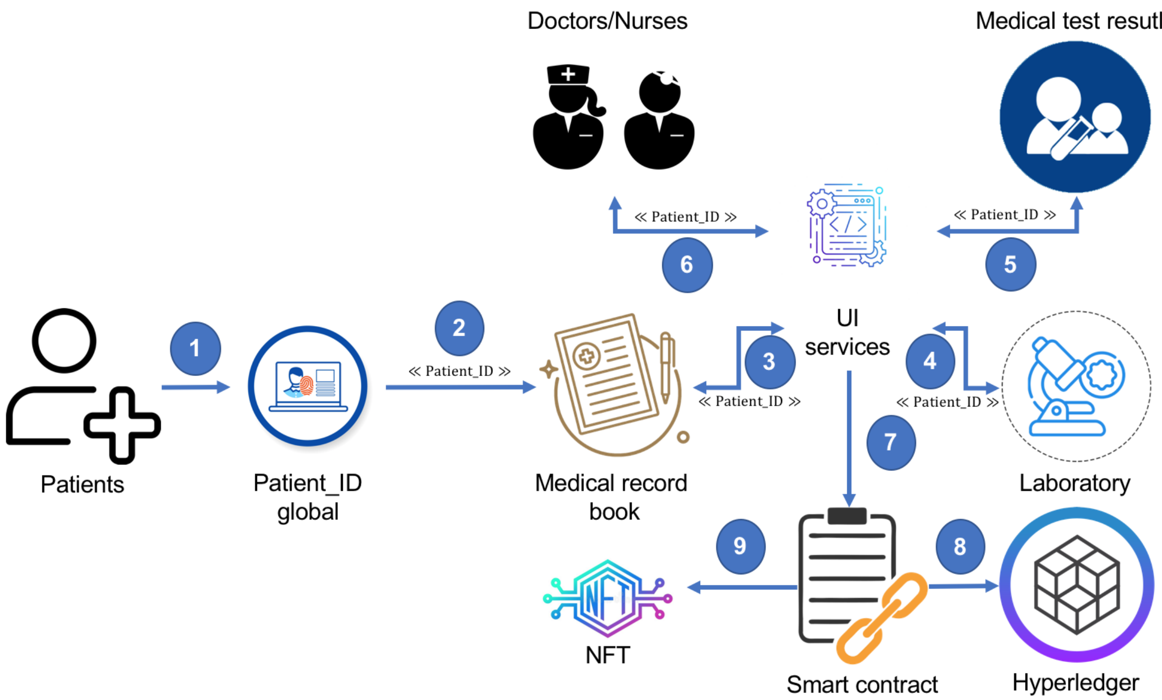


Fig. 2. Medical test results management model leveraging blockchain technology, smart contracts, and NFTs.

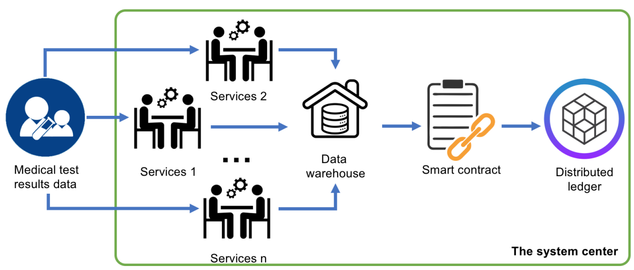


Fig. 3. Initialization of data and Non-Fungible Tokens (NFTs).

```
"results": results of the medical test,
"diagnose": diagnosis of the illness,
"institution": institutionID,
"date": time and date,
"times": times of test,
"period": period of the treatment,
"state": Null
};
```

In particular, besides information useful for content extraction (i.e., medical staff, test results, diagnostic outcomes, etc.), we also store information related to the status of the patient's treatment at the hospital (i.e., "state" - default set to Null). Specifically, the "state" changes to a value of 1 when the respective patient has completed their treatment and exited the medical facility (i.e., `numbers` increment by 1); a value of 0 signifies that the patient is still under treatment. Furthermore, we keep a record of the treatment interval and number of tests conducted through two parameters: "period" and "times".

Following this, pre-designed constraints in the Smart Contract are invoked through the API (i.e., name of function) to synchronize them up the chain. This role of validation carries significant weight as it directly impacts the process of storing medical information (i.e., medical test results), as well as the treatment of patients.

For processes that initialize NFTs (i.e., store only test results), the contents of the NFT are defined as follows:

```
NFT MEDICAL_RECORD = {
"medicalRecordID": medicalRecordID,
"patientID": patientID,
"medicalTestID": medicalTestID,
"type": type of test,
"medicalStaffID": medicalStaffID,
"results": results of the medical test,
"institution": institutionID,
"date": time and date,
};
```

The above-mentioned information is extracted from the original data stored on the chain - our previous model constructed a role-based access control (RBAC) system, hence, direct access from non-owners or unauthorized entities is not possible. Also, considering that a patient undergoes several health assessments/checks before a disease is diagnosed, the information extracted minimizes the risk of data loss. For instance, a doctor diagnosing blood issues does not need access to a patient's bone X-ray.

B. Data Access Procedure

Mirroring the process of data initialization, the method of data retrieval also allows multiple participants to concurrently access the system (i.e., in a distributed model). Assistance

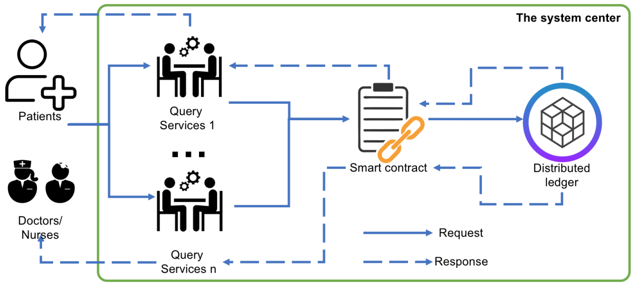


Fig. 4. Data access procedure.

services manage requests coming from medical professionals (like nurses and doctors) and patients who seek to view the data. Depending on the identity of the person making the request, the objectives of access may vary. Specifically, medical personnel might query to validate the procedure of medical testing (i.e., test outcomes), whereas patients might wish to seek details about the current holders of their NFTs.

Fig. 4 showcases the stages involved in retrieving medical test outcome data. These requests are conveyed as services (i.e., pre-configured APIs) from the requester to the existing smart contracts in the system (i.e., function names) before fetching the data from the distributed ledger. All retrieval demands are also kept as access history for each person or entity involved.

If the relevant information cannot be traced (e.g., incorrect ID), the system will return a "results not found" message. Regarding NFT access procedures, all assistance services are provided in the form of APIs.

C. Data Update Procedure

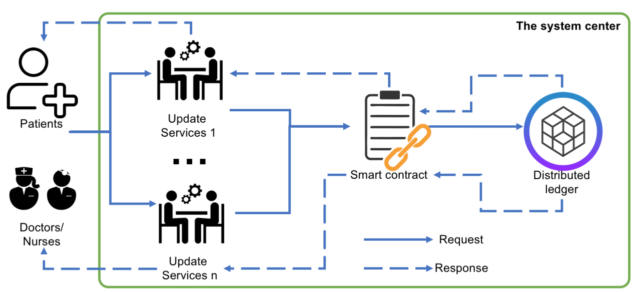


Fig. 5. Data update procedure.

The process of data modification commences only after verifying the existence of the data on the blockchain (i.e., post the corresponding data access procedure). In this segment, we assume that the searched data is present on the blockchain. If the data does not exist, the system sends a "results not found" message to the user (see V-B for further details).

Like the procedures of data access and initialization, we offer modification services as APIs to receive user requests before forwarding them to the smart contract (i.e., function name) for execution. This procedure aims to update test results to minimize patient waiting periods in healthcare institutions. Moreover, it aids doctors in tracing their treatment path based on the associated sequence of NFTs.

Fig. 5 demonstrates the process for modifying medical test results. Concerning NFTs (i.e., available), the update process involves only the transfer from the current holder's address to a new one (i.e., new holder). If any update is made to an existing NFT, it will be registered as a new NFT (refer to V-A for further details).

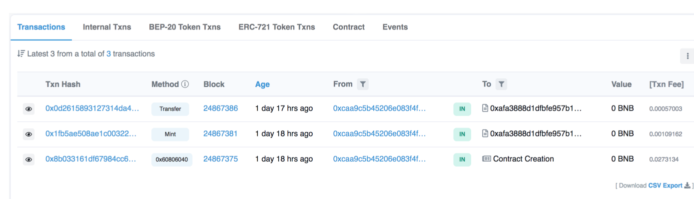
VI. Evaluation Scenarios

The model for generating and managing medical test results is designed to simplify the process for patients. It allows easy management and sharing of medical records with relevant parties. Rather than solely relying on traditional security policies such as access control, we harness the robust and transparent nature of blockchain technology. We chose to leverage Ethereum Virtual Machine (EVM)-enabled blockchain platforms over the Hyperledger ecosystem for its wider accessibility and utilization in existing platforms and systems. Previously, we had assessed system responsiveness, including the number of requests responded to successfully or failed and system latency.

In this paper, we delve into determining the most suitable platform for our proposed model based on economic considerations. Specifically, we implemented a prototype system on four renowned blockchain platforms that support Ethereum Virtual Machine (EVM). The selected platforms include Binance Smart Chain (BNB Smart Chain), Polygon, Fantom, and Celo. Not only did we analyze the performance and cost-effectiveness of these platforms, but we also shared our implementation as a contribution to the wider community.

In these implementations, transaction fees correspond to the supporting coins of the respective platforms. The models were implemented on the 24th of November, 2022 at 8:44:53 AM UTC, with the fees paid in BNB, MATIC, FTM, and CELO, respectively.

A. Binance Smart Chain Implementation and Analysis (sample)



Transactions | Internal Txns | BEP-20 Token Txns | ERC-721 Token Txns | Contract | Events

Latest 3 from a total of 3 transactions

	Txn Hash	Method	Block	Age	From		To	Value	[Txn Fee]
	0x0d2615893127314da4...	Transfer	24867386	1 day 17 hrs ago	0xcaa9c5b45206e083f4f...	IN	0xafa3888d1dfbfe957b1...	0 BNB	0.00057003
	0x1fb5ae508ae1c00322...	Mint	24867381	1 day 18 hrs ago	0xcaa9c5b45206e083f4f...	IN	0xafa3888d1dfbfe957b1...	0 BNB	0.00109162
	0x8b033161df67984cc6...	0x60806040	24867375	1 day 18 hrs ago	0xcaa9c5b45206e083f4f...	IN	Contract Creation	0 BNB	0.0273134

[Download CSV Export]

Fig. 6. The transaction info for BNB smart chain.

We initiated our assessment by implementing the model on the Binance Smart Chain (BNB Smart Chain), and a detailed exploration of the successful installation on this chain is presented in Fig. 6. Binance Smart Chain, as an offshoot of the Binance Chain, offers EVM-compatibility, allowing us to deploy Solidity-based smart contracts with relative ease. It further benefits from its parent chain's high-speed transactions while allowing for better decentralization.

B. NFT Creation Process

Following successful implementation, we explored NFT generation, a pivotal aspect of the proposed model. Fig. 7

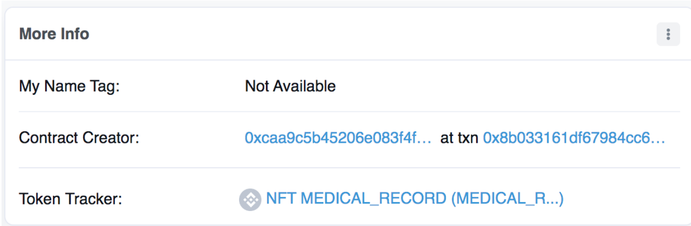


Fig. 7. NFT creation on binance smart chain.

visually demonstrates the creation of an NFT on the Binance Smart Chain. NFTs, inherently unique in their characteristics, perfectly capture the distinct nature of individual medical test results and patient records.

C. NFT Transfer

In line with NFT creation, the retrieval and transfer of these tokens represent the next step in the model's operation. As depicted in Fig. 8, the transfer of NFT ownership addresses occurs smoothly on the Binance Smart Chain. This transferability of NFTs is essential for enabling patients to share their medical test results or records with medical professionals or any other entities of their choice.

In the following sections, we delve into evaluating the transactional aspects of the model, focusing on factors such as transaction fee, gas limit, gas used by the transaction, and gas price. To obtain a comprehensive view of the performance and cost implications of the proposed model, we replicated the same set of operations on the other three selected platforms, namely Polygon, Fantom, and Celo. The underlying motive is to identify the most cost-effective platform for deployment.

Similar settings were used in the remaining platforms to allow for a fair comparison, and the subsequent assessments offer a detailed examination of the transactional metrics. For more detail we refer the reader to check our deployment of the smart contract on the four EVM-supported platforms, namely BNB[9]; MATIC[10]; FTM[11]; and CELO[12].

D. Transaction Fee

In Table I, we dissect the transaction costs associated with creating contracts on all four platforms. It is clearly evident that the most capital-intensive operation across the platforms is contract creation, with BNB Smart Chain exhibiting the highest cost of 0.0273134 BNB ($8.43). Conversely, Fantom's platform reported the most economical contract initiation fee, standing at less than 0.00957754 FTM ($0.001849). The transaction fee for contract creation on Celo's platform was marginally cheaper than that of Polygon, totaling only $0.004 compared to Polygon's $0.01.

Turning our attention to the subsequent two operations, Create NFT and Transfer NFT, the associated costs on all three platforms (Polygon, Celo, and Fantom) are remarkably low, verging on negligible. In stark contrast, the transaction cost on BNB Smart Chain remains considerably higher, amounting to 0.00109162 BNB ($0.34) and 0.00057003 BNB ($0.18) for Create NFT and Transfer NFT, respectively. This disparity underscores the need for an in-depth economic evaluation when selecting a suitable platform for blockchain-based solutions.

E. Gas Limit

Table II showcases the gas limit for each transaction across the platforms. The gas limits for BNB, Polygon, and Fantom remain relatively equivalent, with Polygon and Fantom displaying almost identical figures across all transaction types. Celo, however, sets a significantly higher gas limit, amounting to 3,548,922; 142,040; and 85,673 for contract creation, NFT creation, and NFT transfer, respectively. This discrepancy can have notable implications on the transactional performance and cost-effectiveness of deploying solutions on these platforms.

F. Gas Used by Transaction

Table III illustrates the proportion of the total gas limit consumed by each transaction, as per the figures displayed in Table II. It is noteworthy that BNB, Polygon, and Fantom utilized 100% of the allocated gas limit for the operations of contract creation and NFT creation. Celo's utilization, on the other hand, amounted to 76.92% of the gas limit for these two transactions. When observing the NFT transfer transaction, Fantom and Polygon recorded the highest gas consumption levels at 93.41% of the gas limit, whereas BNB and Celo's consumption stood at 79.17% and 69.8% respectively.

G. Gas Price

As shown in Table IV, the gas price across the platforms remained relatively stable for each transaction type. The BNB Smart Chain showcased the highest gas price, measuring 10 Gwei for all transaction types. Conversely, the Polygon and Celo platforms reflected the lowest gas prices at 2.500000012 and 2 Gwei respectively. Fantom's platform priced gas at 3.5 Gwei, marginally higher than Polygon and Celo, yet significantly lower than the BNB Smart Chain.

H. Summary

In summation, this comparative analysis underscores the essentiality of in-depth cost evaluation before choosing a platform to deploy blockchain solutions. The BNB Smart Chain emerges as the most expensive platform for all transaction types, while Polygon, Celo, and Fantom provide significantly cheaper alternatives. Particularly, Fantom and Polygon offer remarkably low transaction fees and competitive gas limits, making them potentially viable choices for the cost-effective deployment of NFTs. However, consideration should also be given to other critical factors such as platform maturity, ecosystem support, developer experience, security, and user adoption, which are outside the scope of this analysis.

[9]https://testnet.bscscan.com/address/0xafa3888d1dfbfe957b1cd68c36\ede4991e104a53

[10]https://mumbai.polygonscan.com/address/0xd9ee80d850ef3c4978dd0b099a45a559fd7c5ef4

[11]https://testnet.ftmscan.com/address/0x4a2573478c67a894e32d\806c8dd23ee8e26f7847

[12]https://explorer.celo.org/alfajores/address/0x4a2573478C67a894E32D806c8Dd23EE8E26f7847/transactions

	Txn Hash	Age	From		To	Token ID	Token
	0x0d2615893127314da4...	1 day 18 hrs ago	0xafa3888d1dfbfe957b1...	OUT	0xcaa9c5b45206e083f4f...	1	ERC-721: NFT.....ORD
	0x1fb5ae508ae1c00322...	1 day 18 hrs ago	0x000000000000000000...	IN	0xafa3888d1dfbfe957b1...	1	ERC-721: NFT.....ORD

[Download CSV Export]

Fig. 8. NFT transfer on binance smart chain.

TABLE I. TRANSACTION FEE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.0273134 BNB ($8.43)	0.00109162 BNB ($0.34)	0.00057003 BNB ($0.18)
Fantom	0.00957754 FTM ($0.001849)	0.000405167 FTM ($0.000078)	0.0002380105 FTM ($0.000046)
Polygon	0.006840710032835408 MATIC($0.01)	0.000289405001852192 MATIC($0.00)	0.000170007501088048 MATIC($0.00)
Celo	0.007097844 CELO ($0.004)	0.0002840812 CELO ($0.000)	0.0001554878 CELO ($0.000)

TABLE II. GAS LIMIT

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,340	109,162	72,003
Fantom	2,736,440	115,762	72,803
Polygon	2,736,284	115,762	72,803
Celo	3,548,922	142,040	85,673

TABLE III. GAS USED BY TRANSACTION

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,340 (100%)	109,162 (100%)	57,003 (79.17%)
Fantom	2,736,440 (100%)	115,762 (100%)	68,003 (93.41%)
Polygon	2,736,284 (100%)	115,762 (100%)	68,003 (93.41%)
Celo	2,729,940 (76.92%)	109,262 (76.92%)	59,803 (69.8%)

VII. DISCUSSION

A. *Notable Observations*

Our research involving the evaluation and comparison of transaction costs, gas limits, and gas prices across four well-known EVM-compatible blockchain platforms - Binance Smart Chain (BNB), Fantom, Polygon, and Celo - has surfaced several noteworthy findings.

Foremost among them is the cost implication associated with different blockchain platforms. We observed that the Binance Smart Chain tended to levy the highest transaction fees and gas prices, thus potentially raising the cost of blockchain operations for developers and users on this platform. In sharp contrast, Fantom, Polygon, and Celo proved to be more cost-friendly alternatives, with Fantom presenting the lowest transaction fees among the four platforms.

Interestingly, despite lower fees, the gas limits on Polygon, Fantom, and Celo were not vastly different from that of Binance Smart Chain, suggesting that these platforms could potentially be matching the service levels of Binance Smart Chain while also being more economically efficient.

This underscores an important trade-off that users, developers, and companies need to consider when choosing between these platforms: While Binance Smart Chain might be more established and widely accepted, newer platforms like Fantom, Polygon, and Celo are providing compelling value propositions in terms of cost efficiencies, which could lead to considerable savings in the long run.

B. *Threats to Validity*

Despite the informative nature of our study, it is crucial to recognize the limitations and potential threats to its validity.

1) Temporal volatility: The world of blockchain and cryptocurrencies is notably volatile, and costs associated with transactions, gas limits, and gas prices are dynamic, changing in response to a multitude of factors such as market conditions, supply and demand dynamics, among others. Hence, the values presented in this paper may change over time, and users are advised to consider the most recent data while making decisions.

2) Network variations: The state of the network at the time of evaluation could significantly impact the results. Network congestion, often arising due to a surge in demand for transactions, typically leads to an increase in fees, and the reverse is true during periods of lower demand.

3) Platform-Specific variables: Each blockchain platform is uniquely designed, having its own set of characteristics including consensus mechanisms, block time, network size, and more. All these factors can greatly influence transaction costs and gas limits, and our study does not account for these platform-specific variables.

4) Scope constraints: Our analysis included only a limited number of EVM-compatible blockchain platforms and transaction types. Including additional platforms and a wider variety of transaction types could potentially yield different insights and conclusions.

C. *Directions for Future Research*

The findings of this study open up a multitude of interesting directions for future research:

1) Real-time cost analysis: Given the rapid changes in transaction costs in the realm of blockchain, future research could develop a real-time or dynamic analysis model that captures the cost fluctuations across different platforms over a defined period. This could provide more current and actionable insights for users and developers.

TABLE IV. GAS PRICE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.00000001 BNB (10 Gwei)	0.00000001 BNB (10 Gwei)	0.00000001 BNB (10 Gwei)
Fantom	0.0000000035 FTM (3.5 Gwei)	0.0000000035 FTM (3.5 Gwei)	0.0000000035 FTM (3.5 Gwei)
Polygon	0.000000002500000012 MATIC (2.500000012 Gwei)	0.000000002500000016 MATIC (2.500000016 Gwei)	0.000000002500000016 MATIC (2.500000016 Gwei)
Celo	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)

2) Comprehensive performance evaluation: While our study focused primarily on costs, further research could explore other performance metrics such as transaction speed, scalability, security, and reliability. A comprehensive evaluation using multiple performance indicators could help users make a more informed choice of blockchain platform based on their specific needs.

3) Inclusion of other blockchain platforms: Our analysis was confined to a selected few EVM-compatible blockchains. Future research can incorporate more blockchain platforms, broadening the scope of comparison, and providing a more diverse range of options for users to consider.

4) Application-specific evaluation: Another interesting direction could be to investigate the cost and feasibility of deploying specific applications, such as decentralized finance (DeFi), supply chain management, gaming, and more across different blockchain platforms. An application-specific analysis could provide more targeted insights for developers and stakeholders in these domains.

5) Privacy and efficiency implications: In our present examination, we have yet to explore issues associated with the privacy policy of users, such as access control [26], [36] or dynamic policy [41], [42]. These aspects represent potential pathways for future research endeavors. Lastly, methodologies grounded in infrastructure (such as gRPC [43], [44]; Microservices [45], [46]; Dynamic message transmission [47] and Brokerless mechanisms [48]) could be incorporated into our model to boost user interaction, specifically through an API-call-based approach.

In general, our study provides a valuable comparative analysis of transaction costs across different blockchain platforms, which can serve as a useful resource for developers, businesses, and researchers alike. As this area continues to evolve at a rapid pace, continuous monitoring and analysis are crucial to keep up-to-date with the latest developments. Our study provides a foundation upon which more comprehensive, real-time, and application-specific analyses can be built in the future.

VIII. CONCLUSION

In this paper, we have analyzed and compared transaction costs across four prominent EVM-compatible blockchain platforms - Binance Smart Chain (BNB), Fantom, Polygon, and Celo. We evaluated the costs from multiple perspectives, including transaction fees, gas limits, gas used by transaction, and gas prices.

Our research findings reveal significant differences in the transaction cost structure across these platforms. Binance Smart Chain surfaced as the most expensive, with the highest transaction fees and gas prices, while Fantom offered the lowest transaction costs. However, the gas limits across the platforms were comparable, signifying that less expensive platforms could provide a similar level of service as Binance Smart Chain, but at a lower cost. While our research provides valuable insights, it is subject to several limitations, primarily due to the dynamic and rapidly evolving nature of the blockchain landscape. The cost parameters we evaluated are subject to market fluctuations, network congestion levels, and platform-specific variables. Therefore, the results should be interpreted with caution, and users are advised to consider the most current data while making decisions.

Our study opens the door for further research in this domain. Future work could include real-time cost analysis, a comprehensive evaluation of multiple performance metrics, inclusion of more blockchain platforms, and application-specific evaluations. In conclusion, our research underscores the importance of considering transaction costs while choosing a blockchain platform. It provides a clear direction for developers, companies, and researchers, helping them make informed decisions that balance cost and performance. As the blockchain ecosystem continues to grow and evolve, studies like ours will become increasingly crucial in navigating the complex landscape of blockchain platforms and their associated cost structures.

REFERENCES

[1] C.-J. Su and C.-Y. Wu, “Jade implemented mobile multi-agent based, distributed information platform for pervasive health care monitoring,” *Applied Soft Computing*, vol. 11, no. 1, pp. 315–325, 2011.

[2] M. Kyrarini, F. Lygerakis, A. Rajavenkatanarayanan, C. Sevastopoulos, H. R. Nambiappan, K. K. Chaitanya, A. R. Babu, J. Mathew, and F. Makedon, “A survey of robots in healthcare,” *Technologies*, vol. 9, no. 1, p. 8, 2021.

[3] W. H. Organization, *Oral health surveys: basic methods*. World Health Organization, 2013.

[4] A. Rais and A. Viana, “Operations research in healthcare: a survey,” *International transactions in operational research*, vol. 18, no. 1, pp. 1–31, 2011.

[5] K. S. Chan, J. B. Fowles, and J. P. Weiner, “Electronic health records and the reliability and validity of quality measures: a review of the literature,” *Medical Care Research and Review*, vol. 67, no. 5, pp. 503–527, 2010.

[6] X. S. Ha, H. T. Le, N. Metoui, and N. Duong-Trung, “Dem-cod: Novel access-control-based cash on delivery mechanism for decentralized marketplace,” in *2020 IEEE 19th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom)*. IEEE, 2020, pp. 71–78.

[7] X. S. Ha, T. H. Le, T. T. Phan, H. H. D. Nguyen, H. K. Vo, and N. Duong-Trung, “Scrutinizing trust and transparency in cash on delivery systems,” in *International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage*. Springer, 2020, pp. 214–227.

[8] S. Nakamoto, “Bitcoin: A peer-to-peer electronic cash system,” *Decentralized Business Review*, p. 21260, 2008.

[9] ——, "Bitcoin: A peer-to-peer electronic cash system bitcoin: A peer-to-peer electronic cash system," *Bitcoin. org. Disponible en https://bitcoin. org/en/bitcoin-paper*, 2009.

[10] N. Duong-Trung, X. S. Ha, T. T. Phan, P. N. Trieu, Q. N. Nguyen, D. Pham, T. T. Huynh, and H. T. Le, "Multi-sessions mechanism for decentralized cash on delivery system," *Int. J. Adv. Comput. Sci. Appl*, vol. 10, no. 9, 2019.

[11] N. Duong-Trung, H. X. Son, H. T. Le, and T. T. Phan, "Smart care: Integrating blockchain technology into the design of patient-centered healthcare systems," in *Proceedings of the 2020 4th International Conference on Cryptography, Security and Privacy*, ser. ICCSP 2020, 2020, p. 105–109.

[12] ——, "On components of a patient-centered healthcare system using smart contract," in *Proceedings of the 2020 4th International Conference on Cryptography, Security and Privacy*, 2020, p. 31–35.

[13] H. T. Le, K. L. Quoc, T. A. Nguyen, K. T. Dang, H. K. Vo, H. H. Luong, H. Le Van, K. H. Gia, L. V. Cao Phu, D. Nguyen Truong Quoc *et al.*, "Medical-waste chain: A medical waste collection, classification and treatment management by blockchain technology," *Computers*, vol. 11, no. 7, p. 113, 2022.

[14] H. T. Le, L. N. T. Thanh, H. K. Vo, H. H. Luong, K. N. H. Tuan, T. D. Anh, K. H. N. Vuong, H. X. Son *et al.*, "Patient-chain: Patient-centered healthcare system a blockchain-based technology in dealing with emergencies," in *International Conference on Parallel and Distributed Computing: Applications and Technologies*. Springer, 2022, pp. 576–583.

[15] H. X. Son, T. H. Le, N. T. T. Quynh, H. N. D. Huy, N. Duong-Trung, and H. H. Luong, "Toward a blockchain-based technology in dealing with emergencies in patient-centered healthcare systems," in *International Conference on Mobile, Secure, and Programmable Networking*. Springer, 2020, pp. 44–56.

[16] N. H. Tuan Khoi *et al.*, "Vblock - blockchain based traceability in medical products supply chain management: Case study in vietnam," in *International Conference on Artificial Intelligence for Smart Community*, 2020.

[17] N. T. T. Quynh, H. X. Son, T. H. Le, H. N. D. Huy, K. H. Vo, H. H. Luong, K. N. H. Tuan, T. D. Anh, N. Duong-Trung *et al.*, "Toward a design of blood donation management by blockchain technologies," in *International Conference on Computational Science and Its Applications*. Springer, 2021, pp. 78–90.

[18] H. T. Le, T. T. L. Nguyen, T. A. Nguyen, X. S. Ha, and N. Duong-Trung, "Bloodchain: A blood donation network managed by blockchain technologies," *Network*, vol. 2, no. 1, pp. 21–35, 2022.

[19] H. X. Son, M. H. Nguyen, N. N. Phien, H. T. Le, Q. N. Nguyen, V. Dinh, P. Tru, and P. Nguyen, "Towards a mechanism for protecting seller's interest of cash on delivery by using smart contract in hyperledger," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 4, pp. 45–50, 2019.

[20] N. T. T. Le, Q. N. Nguyen, N. N. Phien, N. Duong-Trung, T. T. Huynh, T. P. Nguyen, and H. X. Son, "Assuring non-fraudulent transactions in cash on delivery by introducing double smart contracts," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 5, pp. 677–684, 2019.

[21] H. H. Luong, T. K. N. Huynh, A. T. Dao, and H. T. Nguyen, "An approach for project management system based on blockchain," in *International Conference on Future Data and Security Engineering*. Springer, 2021, pp. 310–326.

[22] N. H. Tuan Khoi *et al.*, "Domain name system resolution system with hyperledger fabric blockchain," in *International Conference on Inventive Computation and Information Technologies*, 2022.

[23] H. T. Le, N. T. T. Le, N. N. Phien, and N. Duong-Trung, "Introducing multi shippers mechanism for decentralized cash on delivery system," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 6, 2019.

[24] Q. N. T. Thi, T. K. Dang, H. L. Van, and H. X. Son, "Using json to specify privacy preserving-enabled attribute-based access control policies," in *International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage*. Springer, 2017, pp. 561–570.

[25] J. Abou Jaoude and R. G. Saade, "Blockchain applications–usage in different domains," *IEEE Access*, vol. 7, pp. 45 360–45 381, 2019.

[26] H. X. Son, M. H. Nguyen, H. K. Vo *et al.*, "Toward an privacy protection based on access control model in hybrid cloud for healthcare systems," in *International Joint Conference: 12th International Conference on Computational Intelligence in Security for Information Systems (CISIS 2019) and 10th International Conference on EUropean Transnational Education (ICEUTE 2019)*. Springer, 2019, pp. 77–86.

[27] M. Misbhauddin, A. AlAbdulatheam, M. Aloufi, H. Al-Hajji, and A. Al-Ghuwainem, "Medaccess: A scalable architecture for blockchain-based health record management," in *2020 2nd International Conference on Computer and Information Sciences (ICCIS)*. IEEE, 2020, pp. 1–5.

[28] G. Zyskind, O. Nathan *et al.*, "Decentralizing privacy: Using blockchain to protect personal data," in *2015 IEEE Security and Privacy Workshops*. IEEE, 2015, pp. 180–184.

[29] Z. Chen, W. Xu, B. Wang, and H. Yu, "A blockchain-based preserving and sharing system for medical data privacy," *Future Generation Computer Systems*, vol. 124, pp. 338–350, 2021.

[30] M. Du, Q. Chen, J. Xiao, H. Yang, and X. Ma, "Supply chain finance innovation using blockchain," *IEEE Transactions on Engineering Management*, vol. 67, no. 4, pp. 1045–1058, 2020.

[31] M. R. Patra, R. K. Das, and R. P. Padhy, "Crhis: cloud based rural healthcare information system," in *Proceedings of the 6th International Conference on Theory and Practice of Electronic Governance*, 2012, pp. 402–405.

[32] C. O. Rolim, F. L. Koch, C. B. Westphall, J. Werner, A. Fracalossi, and G. S. Salvador, "A cloud computing solution for patient's data collection in health care institutions," in *2010 Second International Conference on eHealth, Telemedicine, and Social Medicine*. IEEE, 2010, pp. 95–99.

[33] T. Makubalo, B. Scholtz, and T. O. Tokosi, "Blockchain technology for empowering patient-centred healthcare: A pilot study," in *Conference on e-Business, e-Services and e-Society*. Springer, 2020, pp. 15–26.

[34] Y. Zhang, M. Qiu, C.-W. Tsai, M. M. Hassan, and A. Alamri, "Health-cps: Healthcare cyber-physical system assisted by cloud and big data," *IEEE Systems Journal*, vol. 11, no. 1, pp. 88–95, 2015.

[35] N. M. Hoang and H. X. Son, "A dynamic solution for fine-grained policy conflict resolution," in *Proceedings of the 3rd International Conference on Cryptography, Security and Privacy*, 2019, pp. 116–120.

[36] H. X. Son and N. M. Hoang, "A novel attribute-based access control system for fine-grained privacy protection," in *Proceedings of the 3rd International Conference on Cryptography, Security and Privacy*, 2019, pp. 76–80.

[37] M. M. Madine, A. A. Battah, I. Yaqoob, K. Salah, R. Jayaraman, Y. Al-Hammadi, S. Pesic, and S. Ellahham, "Blockchain for giving patients control over their medical records," *IEEE Access*, vol. 8, pp. 193 102–193 115, 2020.

[38] P. Zhang, J. White, D. C. Schmidt, G. Lenz, and S. T. Rosenbloom, "Fhirchain: applying blockchain to securely and scalably share clinical data," *Computational and structural biotechnology journal*, vol. 16, pp. 267–278, 2018.

[39] V. Patel, "A framework for secure and decentralized sharing of medical imaging data via blockchain consensus," *Health informatics journal*, vol. 25, no. 4, pp. 1398–1411, 2019.

[40] M. Kassab, J. DeFranco, T. Malas, P. Laplante, G. Destefanis, and V. V. G. Neto, "Exploring research in blockchain for healthcare and a roadmap for the future," *IEEE Transactions on Emerging Topics in Computing*, vol. 9, no. 4, pp. 1835–1852, 2019.

[41] S. H. Xuan, L. K. Tran, T. K. Dang, and Y. N. Pham, "Rew-xac: an approach to rewriting request for elastic abac enforcement with dynamic policies," in *2016 International Conference on Advanced Computing and Applications (ACOMP)*. IEEE, 2016, pp. 25–31.

[42] H. X. Son, T. K. Dang, and F. Massacci, "Rew-smt: a new approach for rewriting xacml request with dynamic big data security policies," in *International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage*. Springer, 2017, pp. 501–515.

[43] L. T. T. Nguyen *et al.*, "Bmdd: a novel approach for iot platform (broker-less and microservice architecture, decentralized identity, and dynamic transmission messages)," *PeerJ Computer Science*, vol. 8, p. e950, 2022.

[44] L. N. T. Thanh *et al.*, "Toward a security iot platform with high rate transmission and low energy consumption," in *International Conference on Computational Science and its Applications*. Springer, 2021.

[45] ——, "Toward a unique iot network via single sign-on protocol and message queue," in *International Conference on Computer Information Systems and Industrial Management*. Springer, 2021.

[46] L. N. T. Thanh, N. N. Phien, T. A. Nguyen, H. K. Vo, H. H. Luong, T. D. Anh, K. N. H. Tuan, and H. X. Son, "Ioht-mba: An internet of healthcare things (ioht) platform based on microservice and brokerless architecture," *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 7, 2021. [Online]. Available: http://dx.doi.org/10.14569/IJACSA.2021.0120768

[47] L. N. T. Thanh *et al.*, "Uip2sop: A unique iot network applying single sign-on and message queue protocol," *IJACSA*, vol. 12, no. 6, 2021.

[48] L. N. T. Thanh, N. N. Phien, H. K. Vo, H. H. Luong, T. D. Anh, K. N. H. Tuan, H. X. Son *et al.*, "Sip-mba: A secure iot platform with brokerless and micro-service architecture," 2021.