The following publication Wu, C., Tang, Y. M., Kuo, W. T., Yip, H. T., & Chau, K. Y. (2024). Healthcare 5.0: A secure and distributed network for system informatics in medical surgery. International Journal of Medical Informatics, 186, 105415 is available at https://doi.org/10.1016/j.ijmedinf.2024.105415.

Healthcare 5.0: A Secure and Distributed Network for System Informatics in Medical Surgery

Abstract

Introduction: Health records serve not only as a database of a patient's health history and treatment process but also as a crucial tool for doctors to diagnose and treat patients. However, the storage and sharing of these records are sensitive issues as they involve maintaining patient privacy and ensuring data transparency, security, and interoperability between different parties. Challenges to achieving these goals in the current surgical process can impact the allocation of medical resources and surgical outcomes.

Methods: This article proposes a healthcare 5.0 framework for medical surgery that deploys a secure and distributed network using Blockchain to demonstrate transactions between different parties in the orthopedic surgery process. The proposed network uses the Hyperledger Composer platform for deployment, and a patient-doctor-supplier orthopedic surgery network is designed and implemented to enable the safe sharing of medical records.

Results: A benchmarking tool was implemented for analyzing different scenarios of applying blockchain technology to orthopedic surgery. The application of blockchain technology to orthopedic surgery presents a promising solution for data sharing and supply chain management in the field. The integration of blockchain with cloud storage and hybrid encryption ensures secure and efficient storage of Electronic Health Record (EHR) and Personal Health Record (PHR) data. By leveraging the tamper-proof nature of blockchain and addressing concerns regarding centralized data storage, this scenario demonstrates enhanced security, improved access efficiency, and privacy protection in medical data sharing.

Conclusions: The article demonstrates the feasibility of using an IoT-based blockchain network in orthopedic surgery, which can reduce medical errors and improve data interoperability among different parties. This unique application of blockchain enables secure sharing of medical records, ensuring transparency, security, and interoperability. The network design may also be applicable to other surgeries and medical applications in the future.

***Keywords*:** Blockchain, Healthcare 5.0, Orthopedic Surgery, Electronic Health Records, Hyperledger

1. Introduction

Managing electronic healthcare records (EHRs) in a secure, efficient, and interoperable manner is a critical challenge in the healthcare industry under a high-growth area with significant potential [1]. Traditional centralized information systems used by hospitals restrict data sharing and patient control over their EHRs, limiting the efficient utilization of data [2]. Although virtual reality, artificial intelligence, and information technologies have brought benefits to healthcare, the decentralized nature of patient data and limited data sharing hinder the efficient utilization of data [3,4,5,6]. In contrast, the implementation of blockchain networks offers a solution by decentralizing patient data and enabling secure transactions between different healthcare parties [7]. By leveraging blockchain's distributed ledger technology, healthcare organizations can overcome the limitations of centralized systems, ensuring improved data accessibility and seamless data exchange. his advancement aligns with the Healthcare 5.0 paradigm, which utilizes Internet of Things (IoT) technologies in Industry 4.0, facilitating enhanced data sharing, privacy, security, and interoperability within the healthcare ecosystem [8, 9].

Additionally, blockchain technology offers a decentralized and secure solution, enabling transparent data storage, improved interoperability, and patient empowerment. It facilitates tamper-resistant data recording, secure access control, and seamless information exchange [10]. However, successful implementation requires addressing challenges such as regulatory compliance, scalability, interoperability, and user acceptance [11]. Further research and development are needed to overcome these obstacles and ensure the effective integration of blockchain technology in the healthcare industry.

The research focuses on leveraging blockchain technology to address challenges in data sharing, privacy, security, and interoperability within the healthcare industry, particularly in orthopedic surgery. It aims to achieve several key goals. Firstly, it enables secure and transparent data sharing among patients, surgeons, and implant suppliers, enhancing information transfer and communication efficiency. Secondly, it empowers patients by providing access and control over their electronic healthcare records (EHRs) through the blockchain network, ensuring data security and privacy [12,13]. Finally, the system extends to supply chain management, allowing for the tracking of implants using blockchain technology, and ensuring the security and transparency of the implant supply chain [14].

2. Methods

2.1 Proposed Blockchain Network

In the network design phase, the research focuses on designing a scenario that involves implementing blockchain in the orthopedic surgery process. The existing implant process and blockchain network structure are analyzed to develop a modified process and blockchain structure suitable for the case [15, 16]. The design also includes integrating IoT resources, such as Hyperledger Composer and IoT sensors, into the healthcare network. The participants, assets, organizations, transaction methods, information types, and scope of information access are identified and designed within the project scenario structure. An IoT architecture in a medical system is proposed to present the connectivity and interaction between IoT devices and the blockchain network. The study emphasizes the integration of IoT technology and blockchain architecture in orthopedic surgery. IoT devices, including sensor nodes and intelligent monitors, are utilized to enable precision surgery. These devices facilitate real-time monitoring and data collection during orthopedic surgery, providing accurate information about the patient's physical condition. IoT devices for patients' blood pressure and electrocardiogram readings, as well as IoT devices for implants, are employed to track patients' vital signs and the status of implants. These IoT devices communicate with the cloud computing layer through 5G cellular and satellite communication networks.

To address the challenges of information transparency and trust in orthopedic surgery, the use of blockchain technology is proposed. Blockchain ensures encrypted data sharing and protects the privacy of information. Smart contracts are utilized to create an intelligent model for orthopedic surgery management. It ensures that every step of the process is tamper-proof and traceable, providing transparency and accountability. Reputation and trust mechanisms are adapted to verify transactions in the blockchain-based IoT application. Data generated by IoT devices during surgery are stored as data blocks in the blockchain, enhancing the security and integrity of the information. The blockchain application scenarios in healthcare orthopedic surgery focus on the involvement of patients, surgeons, and suppliers. The process includes authorizing doctors to access patients' records, creating medical records based on physical examinations and MRI scans, placing implant orders, updating order statuses, assigning identifiers to implants, and tracking the order status. Blockchain technology ensures the immutability and transparency of these transactions, enabling secure and efficient coordination between the participants involved.

The basic structure of the blockchain network consists of peers, ledgers, smart contracts, channels, channel configurations, certificate authorities, and applications, as shown in Fig 1. Peers represent participant nodes in different organizations, such as patients, surgeons, and suppliers. Each peer physically holds a full copy of the blockchain ledger, which records all transactions and events. Smart contracts with specific chain codes are installed on the peers, enabling the execution of predefined functions and logic. Channels are used to organize and segregate the participants based on their roles and interactions. The network is regulated by policy rules defined in the network configuration and controlled by organizations and certificate authorities.

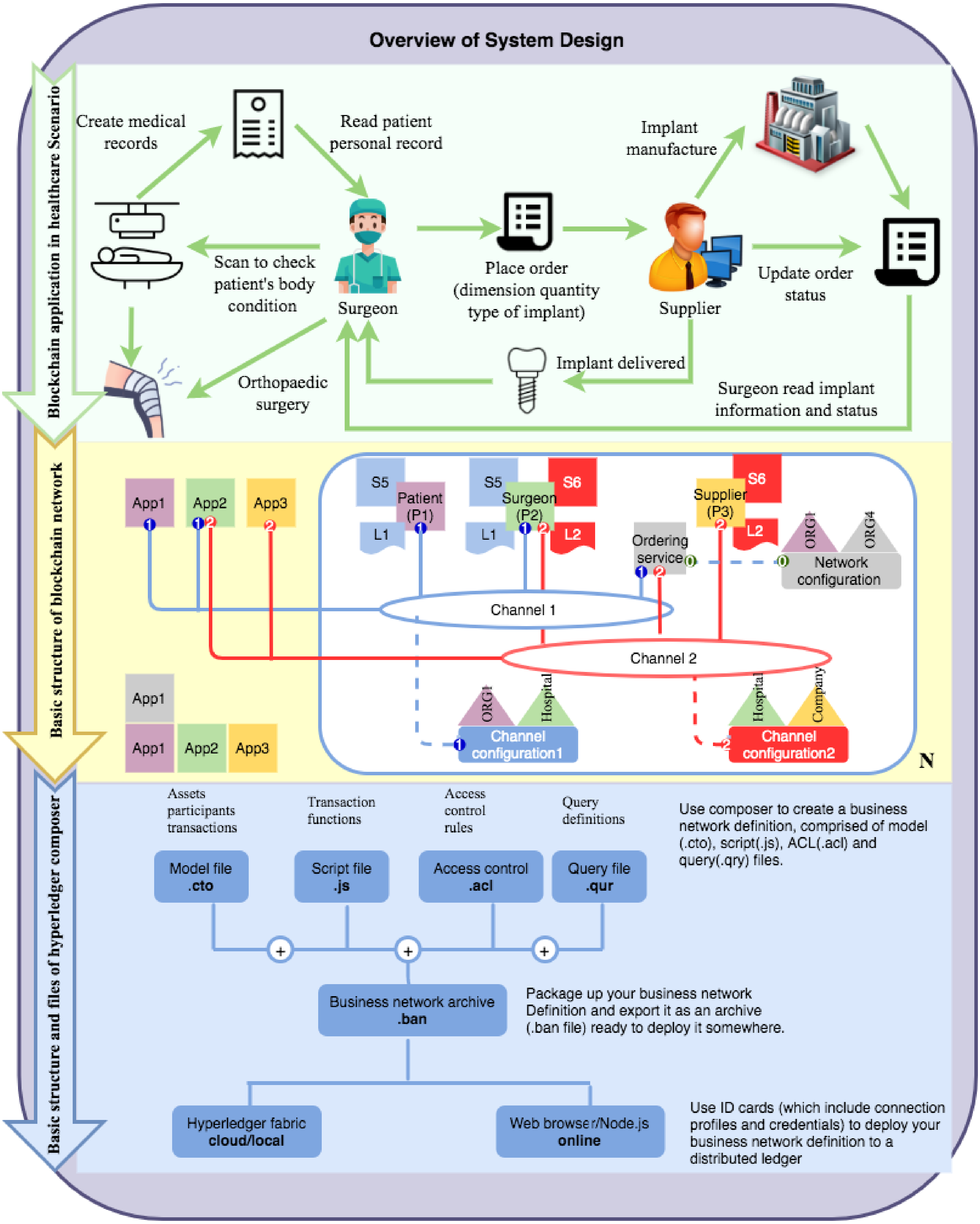

Fig. 1. **The Overview of system design**

2.2. Blockchain Network Design

A blockchain network (Figure 2) consists of different parts: peers, ledgers, smart contracts, channels, channel configurations, certificate authorities, and applications. In this network, there are two channels (C1 and C2) involving different peers (P1, P2, and P3) from different organizations (R1, R2, and R3). Each peer holds a copy of the blockchain ledger (L) and one or more smart contracts (S). Ledger L1 records events in C1 and is hosted by P1 and P2. Peers, ledgers, smart contracts, client applications, and orderer nodes are connected through channels. The network is governed by policy rules specified in network configuration NC4, with control by organizations R1 and R4. Channel C1 is governed by policy rules in channel configuration CC1, controlled by organizations R1 and R2. The ordering service O4 administers the network and supports application channels C1 and C2. Each organization has its preferred certificate authority.

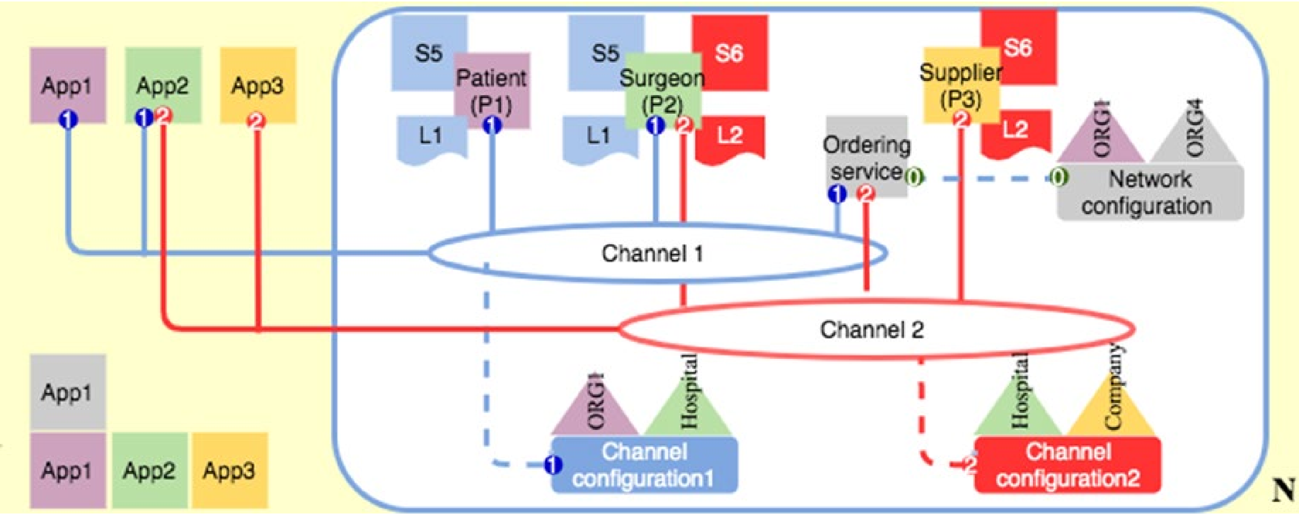

Fig. 2. **Structure of the Blockchain Network**

2.3. System Implementation and Analysis

Hyperledger Composer is used as a tool to efficiently compose and test the required chain code for the orthopedic surgery application. It is chosen as the implementation platform due to its suitability for developing blockchain applications in the proposed scenario. Hyperledger Composer offers a higher-level, intuitive modeling language that enables the design of the business network structure, including assets, participants, and transactions with defined access rights and authority. It provides a comprehensive set of pre-built components, such as access control rules, query files, and script files, which offer ready-to-use functionality for implementing access control mechanisms, executing transactions, and enforcing business rules. Additionally, Hyperledger Composer integrates seamlessly with other Hyperledger frameworks and tools, creating a cohesive ecosystem for building and deploying blockchain networks. It supports interoperability with Hyperledger Fabric, a widely-used blockchain framework in enterprise settings, allowing for the integration of the healthcare blockchain network with existing systems and infrastructure. This integration significantly reduces development time and effort, enabling rapid prototyping and iterative development of healthcare applications.

To implement the system, the required chain code is designed using various components, including model files, script files, access control, and query files. These components play a crucial role in defining the business network structure, encompassing assets, participants, and transactions. The network design also incorporates logical relationships and access control rules for each process and transaction. Once finalized, the implementation is packaged and exported as an archive with a .bna file extension, ready for future deployment processes.

The participants in the network, such as patients, doctors, and suppliers, are assigned unique identifiers and organized under specific organizations. Each participant has a specific level of accessibility to perform actions such as CREATE, READ, UPDATE, and DELETE, allowing them to handle information and execute different transactions based on their roles. In general, patients have full access control over their personal records and can authorize or revoke access for doctors to READ their records through transactions. Doctors have the ability to CREATE and READ order and implant information under specific transactions. Suppliers are granted control over CREATE, READ, and UPDATE actions for implants and orders during certain transactions.

Additionally, the network includes two types of assets: orders and implants, which are created through transactions. Each asset has its own attributes, and only doctors can order and read the status of orders and implants. Script files are written to enable the execution of transactions, update order and implant statuses, and enforce access control rules.

a) Cloud Server

In the implementation process, the cloud is utilized as the platform for running the blockchain network and deployment. The cloud platform enables the execution of sequential transactions on the shared ledger and provides default channels for communication among member companies. Each company possesses a certificate authority (CA) and a peer node responsible for validating and committing transactions. The researchers have outlined the necessary steps for setting up the deployment on the cloud platform, including retrieving the admin secret, creating a CA card, and installing the Hyperledger Composer runtime. Once the network is installed and started, the researchers ensure that the network is running smoothly and functioning properly.

b) Rest Server

REST, also known as Representational State Transfer, is implemented to enable communication between different systems on the web. REST-compliant systems are characterized by their statelessness and the separation of concerns between the client and server. In the REST architectural style, independent development of client and server components is allowed, ensuring that changes to one would not affect the other. By using a REST interface, different clients can access the same REST endpoints, perform the same actions, and receive the same responses.

2.4 Blockchain Network Deployment

The completed business network, named the Patient-Doctor-Supplier network, is ready for testing on the platform. Participants are required to issue unique identities for secure transactions. The business network is exported as a .bna file, which serves as the chain code for deployment. Since a user interface for issuing different identities is not generated, a tailor-made web interface is developed using PHP, also known as Hypertext Preprocessor, which is a widely used scripting language for web development. With PHP, it is possible to write both front-end and back-end structures for the tailor-made web interface, enabling different users to interact with it. The PHP code can call the REST server and, consequently, interact with the Hyperledger Composer fabrics.

To allow various participants to log in to their accounts, the login process includes the creation of index.php and login.php. Upon successful login, users are directed to specific menus based on their roles, such as doctor, patient, or supplier. When users need to update or modify their personal information, they can click the "Update Personal Information" button, enabling patients to modify their details. Additionally, patients can enter the "Authorize Access Form" and input the specific doctor's "userCode" to grant them access. The patient can then view their currently authorized doctor in the form, and doctors are able to read patient records. For revoke transactions, the patient can enter the "Revoke Access Form" and input the doctor's "userCode," resulting in the doctor no longer having authority to access the patient's records. From the doctor's perspective, patient information is displayed in a table format by clicking on the "Read Patient Information" button. By matching the information with the web table, the doctor can easily read the information presented in the table format.

3. Benchmarking and analysis

To demonstrate the feasibility of the proposed blockchain 3.0 and IoT network in the medical system, performance and resource utilization were measured using a benchmarking tool called Hyperledger Caliper. Three scenarios were tested to evaluate the impact of transaction volume, transaction rate, and block time on network performance. Caliper measured transaction success rate, speed, latency, and throughput. Resource utilization metrics, including CPU and memory usage, inbound/outbound transaction traffic, and disk reading, were also analyzed. The success rate represents the number of transactions committed during the test run. Equation (1) calculates transaction speed, equation (2) measures transaction latency, and equation (3) defines transaction throughput (TPS). These equations help quantify the performance of transactions in terms of speed, latency, and successful transaction rate.

$$Transaction\ Speed = \frac{Number\ of\ Committed\ Transaction}{Transaction\ Time} \quad (1)$$

$$Transaction\ Latency = Transaction\ Committed\ Time \times Network\ Threshold - Request\ Time \quad (2)$$

$$Transaction\ Throughput = \frac{Committed\ Transactions}{Total\ Transaction\ time} \times Committed\ Node \quad (3)$$

The benchmarking environment was deployed on a virtual machine running Ubuntu Linux 18.04 LTS. The virtual machine had an AMD Ryzen 7 5800H processor, 8 GB of memory, and 100 GB of storage. Hyperledger Fabric, Docker Engine, and Docker Composer were installed and configured on this virtual machine. Hyperledger Fabric was installed using the curl tool and managed with Node Package Manager (npm). The necessary components for organization and peer node setup were included in the Docker engine. In this work, various languages and libraries were utilized, including Go Language (GoLang), Python, and Node.js, to support different aspects of the project.

3.1 Simulation Scenarios

To analyze the performance and resource consumption of the various configurations. Three distinct scenarios are presented to simulate the reality of an electronic health record system for patients, hospitals, and suppliers.

a). Scenario 1: Effect of number of transactions on different network size

In scenario one, the effect of transaction numbers on network size was investigated. The simulation's configurations are listed in Table 1. This scenario attempted to determine the workload of blockchain transactions in various channel structures, simulating the structure and workload of several health record systems. Fig. 2 illustrate the outcomes for reading and writing requests, respectively.

TABLE 1

Configuration and description on simulation scenario one.

Configuration	**Description**
Scenario	1
Network Size*	1 Org 1 Peer each, 2 Orgs 1 Peer each, 2 Orgs 2 Peers each, 4 Orgs 1 Peers each
Number of Transaction*	500 tx, 1000 tx, 2000 tx, 4000 tx
Transaction Rate	50 TPS
Block Time	2000 ms
Transaction Mode	read & write
Performance metrics	Transaction Latency, Transaction Throughput
Resource utilization	N/A

*: varied factors

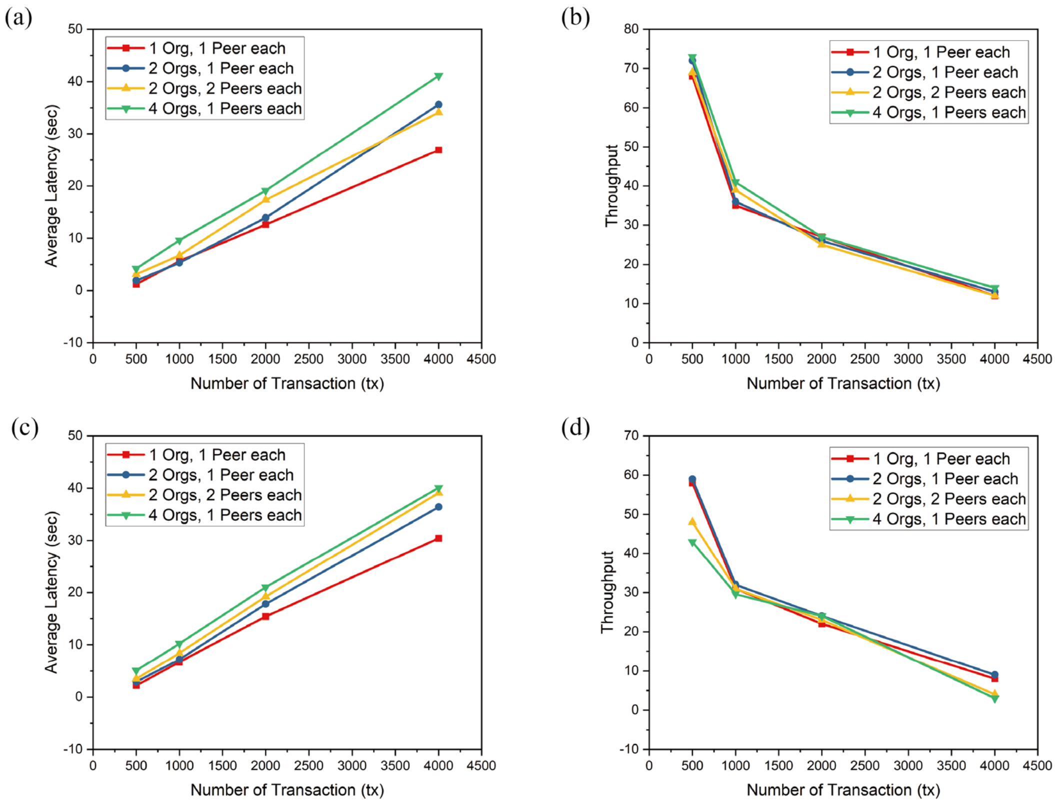

Fig.3. The average latency (a)(c) and throughput (b)(d) in scenario one on the effect of number of transactions on different network size for reading request

As a result, the average latency of both reading and writing requests increases as transaction numbers increase, but network size shows no significant impact. Reading and writing requests have similar delays, indicating a modest effect of transaction numbers on delay. Throughput decline dramatically between 500 and 1000 transactions and continues to decline steadily. Both reading and writing requests exhibit declining patterns, with writing requests having significantly lower throughput.

b). Scenario 2: Effect of block time on different network size

In scenario two, the investigation of the effect of block time on different network sizes is done. The configurations of the simulation are shown in table 2. This scenario was looking for the optimum wait time of each transaction under the same number of transactions and transaction rate for different network sizes. The results are shown in Fig. 3 for the writing request.

TABLE 2

Configuration and description on simulation scenario three.

Configuration	**Description**
Scenario	3
Network Size*	1 Org 1 Peer each, 2 Orgs 1 Peer each, 2 Orgs 2 Peers each, 4 Orgs 1 Peer each
Number of Transaction	500 tx

Transaction Rate	50 TPS
Block Time*	2000 ms, 250 ms
Transaction Mode	Write
Performance metrics	Transaction Latency, Transaction Throughput
Resource utilization	N/A

*: varied factors

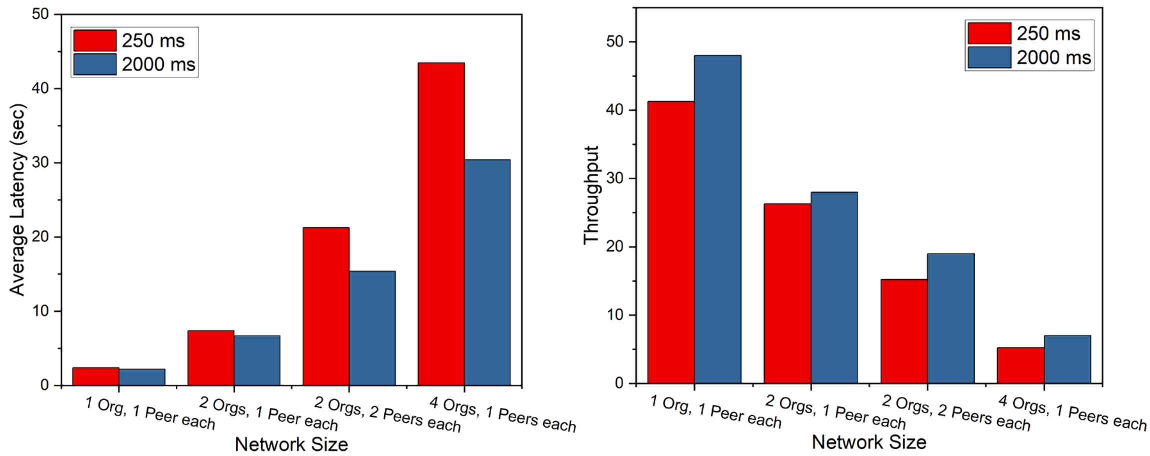

Fig.4. The average latency (left) and throughput (right) in scenario three on the effect of block time on different network size for writing request

The block timeout sets the maximum time before pending transactions are included in a new block. A shorter block timeout increases delay and reduces throughput as the block production slows down, requiring more block numbers for committed transactions [17], leading to increased latency and decreased throughput.

c). Scenario 3: Effect of number of transactions on different input transaction rate

In the final scenario, the influence of transaction numbers on various input transaction rates is investigated. The simulation's settings are shown in Table 3. This scenario attempted to optimize the number of transactions and the pace of input transactions within the same channel node setup. Fig. 4 illustrate the outcomes for reading and writing requests, respectively.

TABLE 3

Configuration and description on simulation scenario one.

Configuration	**Description**
Scenario	4
Network Size	4 Orgs, 1 Peers each
Number of Transaction*	500 tx, 1000 tx, 2000 tx, 4000 tx
Transaction Rate*	50 TPS, 100 TPS, 150 TPS, 200 TPS, 250 TPS
Block Time	2000 ms
Transaction Mode	Read & write
Performance metrics	Transaction Latency, Transaction Throughput
Resource utilization	average CUP%, average Memory

*: varied factors

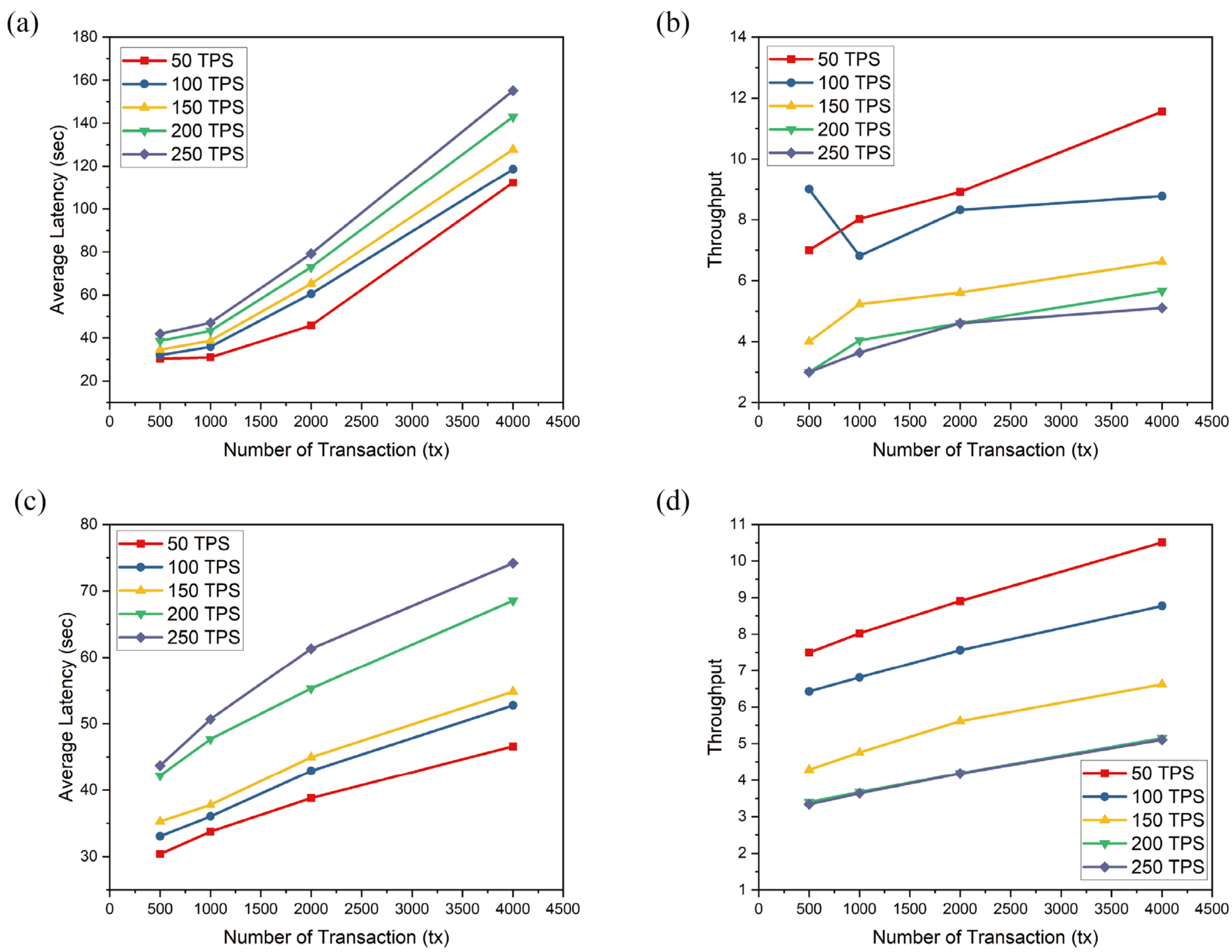

Fig.5. The average latency (a) (c) and throughput (b) (d) in scenario one on the effect of number of transactions on different network size for reading request

To begin, both reading and writing requests exhibit the same pattern: the greater the transaction rate, the higher the average latency and throughput, while a larger transaction count results in increased delay and throughput. With a predefined greater transaction speed, more transactions may be committed in each block, resulting in a better successful transaction ratio.

TABLE 4

The resources utilization result in scenario one on the effect of transaction rate on different network sizes in terms of average CPU % consumption and average memory consumption.

Number of Transaction	**Transaction Rate (TPS)**									
	50	**100**	**150**	**200**	**250**	**50**	**100**	**150**	**200**	**250**
	Read Transaction Mode					**Write Transaction Mode**				

Average CPU (%)										
500 tx	39.9	44.7	42.8	43.7	47.1	45.5	47.3	43.6	45.9	51.3
1000 tx	41.9	42.7	46.7	45.1	40.3	55.9	54.0	46.7	50.9	57.0
2000 tx	52.3	51.9	54.3	61.0	52.3	61.5	65.3	55.5	59.1	65.0
4000 tx	65.8	67.8	69.0	70.6	77.4	74.5	81.6	70.5	72.1	78.6
Average Memory (MB)										
500 tx	88.2	86.2	82.3	86.2	82.3	98.8	96.6	88.9	92.3	89.7
1000 tx	90.0	97.9	102.3	104.1	111.1	112.6	107.2	96.9	114.4	99.6
2000 tx	120.0	124.4	134.9	137.6	149.9	126.1	129.7	126.0	130.4	124.5
4000 tx	158.8	162.3	167.6	179.0	185.2	147.6	154.4	158.7	153.9	149.4

The distribution of resource use by transaction rate and the number of transactions is shown in Table 4. The increased average CPU and memory use were due to the increased volume of data and queries being sent to the database and channel for ordering and acknowledgment. This significantly increases the system's resource use.

4. Discussion

Healthcare 5.0 has diverse applications in e-healthcare system [18], personal health record sharing [19], medical research [20,21], and supply chain management. However, few studies have applied blockchain technology to surgical procedures. This research aims utilizes blockchain technology to enhance orthopedic surgery process by improving transparency, security, privacy, and interoperability. Patient-controlled access and a permissioned blockchain structure are implemented, allowing patients to authorize and revoke data access. This enhances patient privacy and ensures consistent access to health records for information seekers or doctors, fostering interoperability and data sharing between patients and healthcare organizations.

Further, some studies combine blockchain technology with the supply chain management of devices and drugs. Attili et al. [22] proposed solutions to improve the identification, monitoring, and prevention of counterfeit drugs in the supply chain. Tseng et al. [23] used blockchain as the basis for drug data flow to create transparent data on drug transactions to prevent counterfeit drugs. This paper mainly refers to the application of blockchain in the supply chain management of pharmaceuticals and implants. Every manufactured implant in this system holds a unique identifier, helps keep track of, and issues several updates on the status to utilize the power of the smart contract. The tracking process is important for the quality management and security of the implant information, reducing the chance of malicious tampering on the status of orders or implants.

For sharing data among different parties, blockchain technology provides security. Zyskind et al. [24] mainly used blockchain technology for data access and security management, allowing different parties to store and run calculations on data while keeping the data private. This research is mainly based on the data structures and properties of blockchain technology, what the data are encrypted on the peer-to-peer network using Merkle Tree and hash functions, and become effective in detecting any changes even if only a piece of modified data. This greatly improves the security of data passing between different parties and reduces the chances of data exposure. The blockchain application allows immediate data sharing among different nodes in the same blockchain network. When users have the granted access right, it improves transparency and interoperability, and even helps to maintain the trust relationship among different healthcare parties.

5. Conclusions

The establishment of a healthcare information platform using blockchain is a promising solution for addressing current issues such as medical information silos, inadequate security of medical electronic data, and unequal distribution of medical resources. The decentralized and tamper-proof nature of blockchain enables secure sharing and storage of medical data, promoting information sharing, data security, and telemedicine. This paper presents a scenario that applies blockchain to orthopedic surgery, facilitating data sharing and supply chain management for implants. The system was deployed using Hyperledger Composer on a cloud platform, ensuring privacy through hybrid encryption. The tamper-proof functionality and blockchain storage enhance data security. This practical application of blockchain provides a secure and efficient solution for medical data sharing.

However, there are limitations and potential areas for future research. The business network deployment lacks a comprehensive user interface due to outdated node modules, necessitating the use of additional PHP files to enhance the user experience. In this study, we examined the influence of four prevalent setups in this area. The impact of transaction counts on performance within channels is negligible, while the input transaction rate has a significant boosting effect. Configurations with more pre-defined transactions and higher transaction rates increase latency but also improve throughput. The study's simulations were limited to a few predefined configurations. To further enhance performance and optimize resource consumption, future research should focus on refining the user interface and exploring different blockchain types for other surgical procedures. Further investigations should include comprehensive performance analysis and prediction based on various configurations to optimize resource consumption.

6. Summary table

What is already known on the topic:

- Blockchain technology enables a secure, accurate, and efficient share healthcare data which benefits society
- It promotes technology that directs the exchange of digital assets between different parties

What did this study added to the body of knowledge?

- The Blockchain 5.0 network revolts digital health and medical system for information integration
- The informatics enable share and update patient medical records in a seamless and complete process

Declarations of interest

The authors have no conflicts of interest to disclose.

Acknowledgements

We would like to acknowledge the support of the Department of Industrial and Systems Engineering from the Hong Kong Polytechnic University, Hong Kong and the City University of Macau for the enhancement of this article.

Formatting of funding sources

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

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