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Blockchain-based Medical Image Sharing and Critical-result Notification

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Blockchain-based Medical Image Sharing and Critical-result Notification

A Thesis Presented To
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ABSTRACT

In teleradiology, medical images are transmitted to offsite radiologist for interpretation and the dictation report is sent back to the original site to aid timely diagnosis and proper patient care. Although teleradiology offers excellent benefits such as time and cost efficiency, after-hour coverages, and staffing shortage management, there are some technical and operational limitations to overcome in reaching its full potential. Lack of system integration has been one of the main challenges. Therefore, we analyzed the current teleradiology workflow to identify the challenges stemming from the disparate systems. Image unavailability and delayed critical result communication are caused by lack of integrated systems between teleradiology practice and healthcare institutions and they are among the most substantial factors causing prolonged radiology turnaround time. This thesis proposes a blockchain-based platform for efficient and secure medical image sharing and critical-result notification to address those limitations. We believe that the proposed platform will improve efficiency in medical image sharing and collaboration between physicians and radiologists and benefit patients with reduced turnaround time. While considerable progress has been achieved in healthcare blockchain, further research on governance and HIPAA compliance is required to optimize the adoption of the new technology.

Keywords: *Blockchain, Hyperledger Fabric, Teleradiology, Medical Image Sharing, Critical-Result Notification, Workflow Automation, Process Improvement*

CHAPTER I.

INTRODUCTION

Teleradiology is a branch of telemedicine [1]. It refers to a practice where radiologists interpret radiological studies offsite from where the studies are generated. In teleradiology, medical images are transmitted electronically to offsite radiologists (teleradiologists), and dictation reports are sent back to the original site to aid proper patient care [2]. Teleradiology offers excellent benefits of time and cost efficiency, after-hours coverages, and staffing shortage management to improve the quality of patient care, healthcare system efficiency, and radiologists' productivity [3]. Thus, it is widely used for hospitals, imaging centers, emergency facilities, and mobile x-ray services, and commercial radiology outsourcing enterprises have been emerging. The field's growth has accelerated as telehealth gains popularity during the recent COVID-19 pandemic [4]. With this trend, the global teleradiology market size was estimated to be $3.453 billion in 2019 and is expected to reach $8.024 billion by 2026 [5].

Despite their apparent promise, there are some limitations in reaching the full potential of teleradiology. Systems integration has been one of the main challenges as image management system resides in the onsite information system security domain, and teleradiology practice has its own system [6]. Working with disparate systems causes challenges in medical image transmission and critical result communication between teleradiology practice and other health care institutions. In addition, teleradiologists often do not have direct access to the onsite Radiology Information System (RIS) or Picture Archiving and Communication System (PACS); instead, they use web-based image distribution systems [3], [7].

This can be problematic because the web-based image distribution systems offer limited functions compared to those used by onsite radiologists. In addition, teleradiologists have limited access to patient history as they do not have direct access to RIS; thus, they can only provide provisional reports in some cases. Furthermore, current image transmission operates on the "demand-push" model, where the sending site needs to initiate image transmissions. So, if images are missing from the image set or prior images are needed for comparison, teleradiologists must request the sending site to resend those data [3]. Lastly, a lack of an effective platform to communicate critical findings can affect patient outcomes as timely patient management is crucial for survival rates and reducing complications in the care of critically ill patients.

The challenges mentioned above cause inefficiencies in the workflow and interruptions in radiologists' workflow. This thesis will examine the current teleradiology workflow focusing on identifying the pain points in image sharing and critical result communication. We will then propose a blockchain-based model for image sharing and critical-result communication to address current limitations in teleradiology.

The remainder of the thesis is structured as follows: Section II provides an overview of previous research on healthcare blockchain applications and a brief introduction to Hyperledger Fabric. Section III discusses challenges in the current teleradiology workflow. Section IV presents a proposed architecture and prototype of the application for a blockchain-based medical image sharing and critical-result notification application.

Section V discusses the advantages and limitations of the prototype, and Section VI concludes the thesis.

CHAPTER II.
RELATED WORKS

A. Literature Review

Although there is an increasing interest in blockchain technology from healthcare, there are limited use cases and research on the use of blockchain in healthcare compared to other industries, especially in radiology. Healthcare blockchain applications are primarily at the conceptual stage, and many of them focus on managing EHR (Electronic Health Records) or medical research data.

A. Azaria et el. [8] proposed blockchain-based medical data access and permission management system, MedRec. MedRec is the first to develop a fully functional blockchain prototype to address the challenges in current EHR systems such as data fragmentation, data accessibility, system interoperability, patient agency, and quality and quantity of medical research data. Each node in the blockchain network only stores copies of authorization data while medical records are stored on external databases. It utilizes data pointers to retrieve distributed medical records and Ethereum's smart contracts for permissions, data sharing, and mining. Its smart contract structure consists of Register Contract (RC), Patient-Provider Relationship Contract (PPR), and Summary Contract (SC). RC regulates new identity registration and maps IDs with their Ethereum addresses.

PPR defines data ownership and stewardship between patient and provider, access information such as data pointers and access permissions, and mining bounties for researchers. Finally, SC is a ledger with all references to PPR contracts. Each node consists of backend API library, Ethereum client, database gatekeeper, and EHR manager and is managed via a web user interface. The backend library aids communication between the user interface and the Ethereum client. The database gatekeeper verifies a query request and returns the query result to the user. When a provider adds a new patient, the backend library communicates it to the Ethereum client. The Ethereum client utilizes RC to create a new PPR contract defining the provider's data stewardship for the patient's medical record. The patient's SC gets updated with the new PPR contract. Hence, every time a provider requests stewardship for their medical data, the patient will get an alert to grant or deny the request. This way, patients keep ownership and complete control of their records.

S. Abdullah et el. [9] suggested potential blockchain use cases in radiology such as authentication and verification, administrative and governance, and research and machine learning. Examples of blockchain usage for authentication and verification include image sharing access control, health data network authentication, and imaging data verification. Blockchain can also manage claim adjudication, billing, supply chain, imaging equipment maintenance, and inspection record-keeping for administrative and governance purposes. In addition, blockchain can enhance data sharing for research, clinical trials, machine learning training, and AI model execution. An imaging sharing company, NucleusHealth (San Diego, CA, USA) [10] uses Ethereum blockchain to create access control rules for image sharing between two systems. Patient health information (PHI) is neither stored on the blockchain nor is medical imaging data transferred within the network. Instead, this Ethereum-based image sharing application allows image viewing utilizing DICOM Web URL and DICOMWeb RESTful API while keeping the images at the site's resource location. In addition, unique exam IDs are stored in the blockchain with the patient attached to the exam, and smart contract allows patients to share their images by granting access.

M. Jabarulla and H-N Lee [11] proposed a patient-centric image management system using an Ethereum blockchain and Inter-Planetary File System (IPFS)-based decentralized framework to solve the current system's challenges, including privacy, security, access flexibility, and costs. It stores and shares access to medical images within an open distributed network while offering transparency and patients' complete control over their images. In addition, smart contract was used to enable patient-centric access management, through which patients can grant/revoke access to their providers.

B. Shen et el. [12] mentioned scalability and latency as one of the top barriers to adopting existing blockchain applications and suggested a session-based data sharing using blockchain to address the problem. MedChain connects healthcare organizations through a decentralized network comprising two different peer modes: super peers and edge peers, enabling session-based data sharing among peers. Super peers provide computing and storage resources for the data-sharing infrastructure, while edge peers store patient data. Modules of super-peer consist of blockchain service, directory service, and healthcare database. The blockchain server keeps records of data sharing to provide data integrity and auditing, while the directory server manages patient data inventory and data sharing sessions. These servers form sub-networks. The healthcare database stores patient data. The event is recorded in the blockchain when the data description for new data is added to the directory service. When providers request a patient's data, they select the data from their inventory to share, creating a session. The blockchain service adds the session in a new block and issues a session ID with which providers access the data.

Like healthcare blockchain applications mentioned above, there have been use-cases and research on improving patient-centric healthcare data sharing and management using blockchain [13], [14]. However, few researchers have considered utilizing blockchain to improve workflow efficiency. In this thesis, we want to improve workflow efficiency in teleradiology with blockchain technology. Our proposed blockchain-based medical image sharing and critical-result notification application will address the current challenges of teleradiology workflow and provide a potential solution for optimizing the workflow.

B. Overview of Hyperledger Fabric

Hyperledger Fabric is an open-source framework for permissioned blockchain networks [15], [16]. A permissioned network operates on a closed network, and all participants have known identities, unlike a public network where anyone can enter the network to see the transaction records. Furthermore, Hyperledger Fabric offers technical advantages to achieve enhanced performance, scalability, security, and privacy for healthcare data. For example, its modular architecture provides optimized performance, scalability, and levels of trust, and the data partitioning function that it provides through channels enables enhanced confidentiality and privacy of data [17]. Hyperledger network consists of peer nodes, certificate authorities (CA), membership service providers (MSP), chaincode (smart contract), channels, assets, organizations, and ordering service. Each participant has a copy of the shared ledger that comprises the world state that describes the current state of the ledger and the transaction log that records all transactions [18].

- Immutability and integrity of data: Each member has a copy of the ledger. Distributing the ledger among members prevents a single point of failure and guarantees immutability and integrity.
- Identity management: MSP manages user authentication and authorization through digital certificates.
- Privacy and confidentiality: Channels can be created among a group of network members to keep specific transaction data private and confidential.
- Speed and accuracy: Smart contract define business logic as executable code and automates transactions eliminating the need for intermediaries.

CHAPTER III.

CHALLENGES IN CURRENT TELERADIOLOGY WORKFLOW | MOTIVATION

Radiological exams are one of the key diagnostic tools that visualize the inner body structures to provide anatomic details of the patient. Therefore, getting a radiology report on time is crucial for timely patient care and disease management. Reducing radiology report turnaround time can significantly impact patient outcomes, especially in critical conditions like stroke, acute pulmonary embolism, or intracranial hemorrhage. We analyzed teleradiology's current workflow to identify pain points that cause delays in workflow and interrupt radiologists during image dictation. Workflow analysis was performed based on the author's direct work experience as a radiology worklist specialist and interviews with a radiologist and a support team member.

A radiologist works with three applications: worklist, image viewer, and a voice dictation tool. The worklist provides patient history, exam information, and a link to open images in the image viewer. Radiologists also use the worklist to communicate needs for additional/missing images or critical result notifications by opening a ticket. When a new ticket is created, a support team member contacts the site to get the requested images or to connect the radiologist with the referring physician. Currently, these requests are communicated manually through phone calls and require collaborations between onsite and offsite personnel. As a result, delays and interruptions can occur on both clinical and radiologists' sides.

A. Image Unavailability; missing images/additional images

As the introduction mentions, teleradiologists do not have direct access to the sending site's RIS or PACS [3]. As a result, they can only review images once the originating site sends them, creating potential image unavailability and inefficiencies in the workflow. For example, radiologists must request and wait for images when they receive incomplete image sets or need prior exams. Another instance would be that radiologists must request to check data completeness when a study contains fewer images than standard image sets. Each site has its imaging protocols; thus, the total number of images for a study can differ. It is hard for radiologists to know whether fewer images are from data lost in transit or the site's imaging protocol for that specific order. Therefore, radiologists create a ticket from the worklist to communicate these needs.

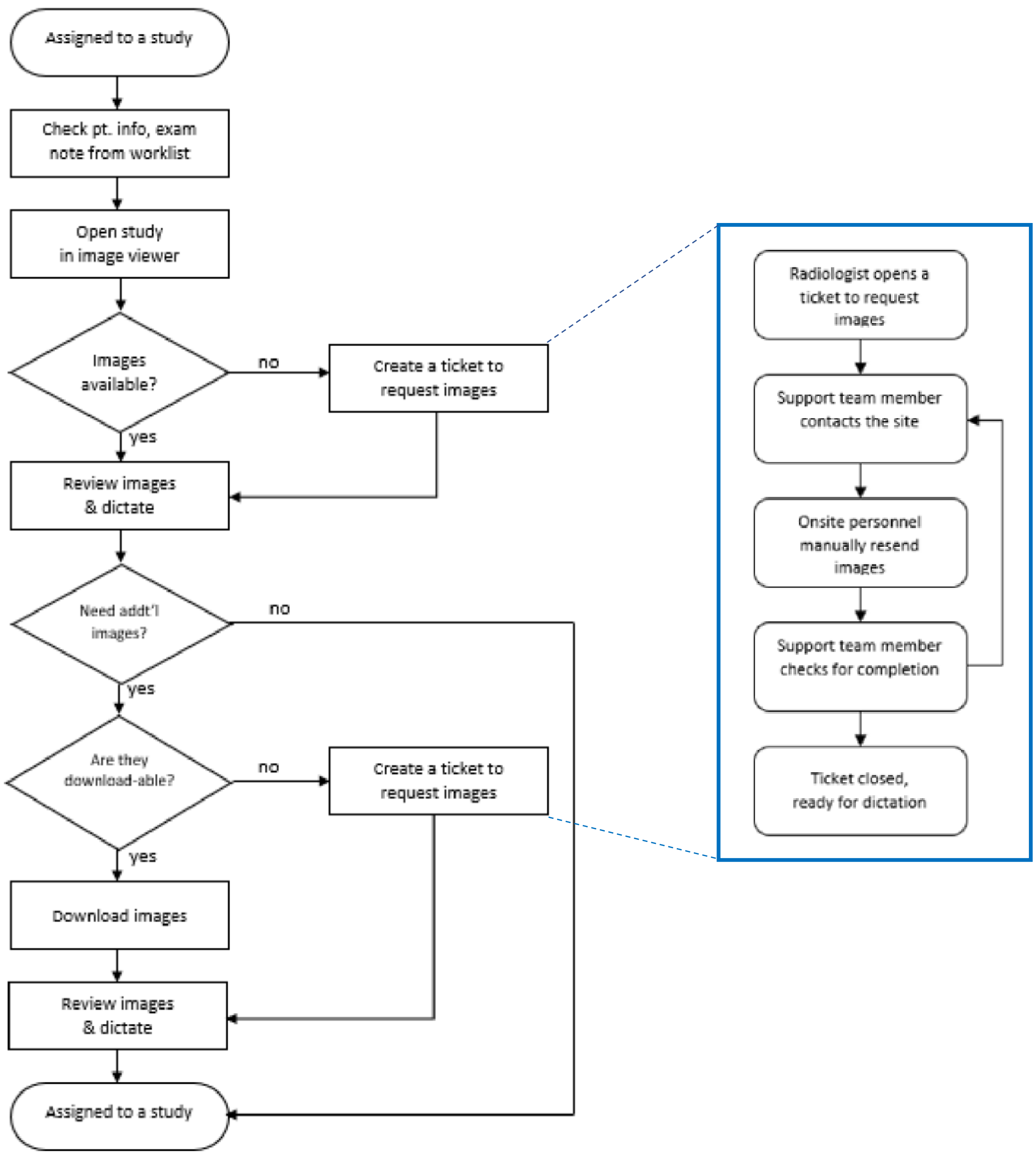

Figure 1: Current workflow for image request tickets

As shown in Fig.1, once a teleradiologist opens a ticket to request missing/prior images, a support team member contacts the site asking to resend the images. Upon receiving the requested images, the support team member closes the ticket and makes the exam available for the radiologist to interpret. This process may sound simple; however, it can take up to 20-30 minutes in real-world scenarios as it involves multiple personnel, both onsite and offsite, requiring phone calls and voice mails. Moreover, getting additional phone calls and resending images are an extra workload for clinicians that can negatively impact their workflow.

B. Delayed critical result communication

Critical conditions require immediate medical attention. Therefore, these critical findings need to be conveyed promptly. The current process for critical result communication is the same as image requests mentioned above; a radiologist requests a critical connection through a ticket from the worklist. Then, a support team member contacts the site to connect the teleradiologist with the provider. Although critical connect request prioritizes others, delays still happen due to difficulty reaching the referring physician or simply from a large ticket volume.

Blockchain technology can be a potential solution to address these problems. Our proposed blockchain-based medical image sharing and critical result notification model offers an efficient way to share medical images and communicate critical findings to improve radiologists' workflow efficiency and reduce radiology report turnaround time.

CHAPTER IV.

PROPOSED ARCHITECTURE | PROTOTYPE

A. Proposed Architecture

We have developed an architecture to improve image availability and critical-result notifications. The proposed architecture provides a private and permissioned network with all participants having known identities, and its technical advantages support enhanced performance, scalability, security, and privacy. Hyperledger Fabric can be a suitable implementation for the proposed architecture.

Healthcare blockchain applications mentioned in the Literature review used Ethereum. Their focus is on patient-centric EHR management, and Ethereum is a suitable choice in this case as its strength lies in smart contracts, decentralization, and user empowerment. However, Hyperledger Fabric is to enhance collaboration in developing cross-industry blockchain technologies. Thus, its functionality and performance align better with our goal of optimizing workflow in business-to-business collaboration.

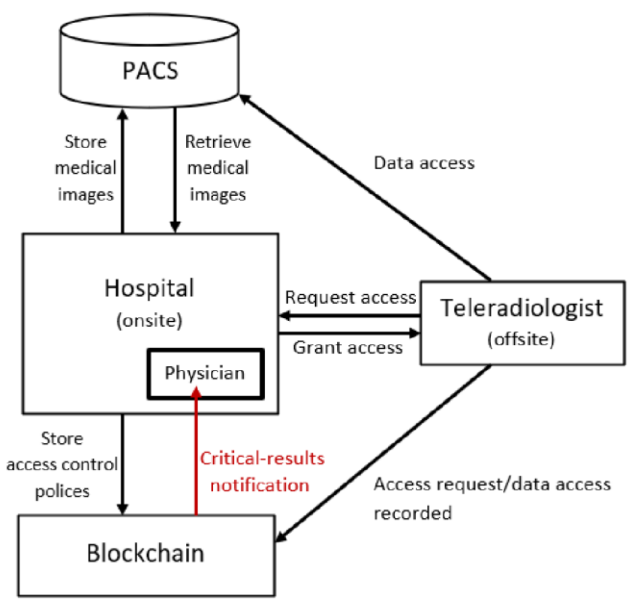

Figure 2: Proposed architecture

Figure 2. shows our conceptual model for blockchain-based medical image sharing and critical-result notification application. This model comprises users (radiologists, physicians), organizations (hospitals), onsite Picture Archiving and Communication System (PACS), and blockchain networks. All medical images will be stored off-blockchain in the onsite PACS, and the blockchain controls and manages access to the onsite PACS [19], [20]. Radiologists must register through their user application first to request and view images. Once the onsite administrator approves a radiologist's registration, the radiologist can request access to medical images. When a radiologist submits a request to access medical images, peer nodes in the hospital verify the authenticity of the access request. The radiologist will be provided with a link to the requested images if access is granted. Hash is created for every request and data access and gets recorded in a block in the blockchain.

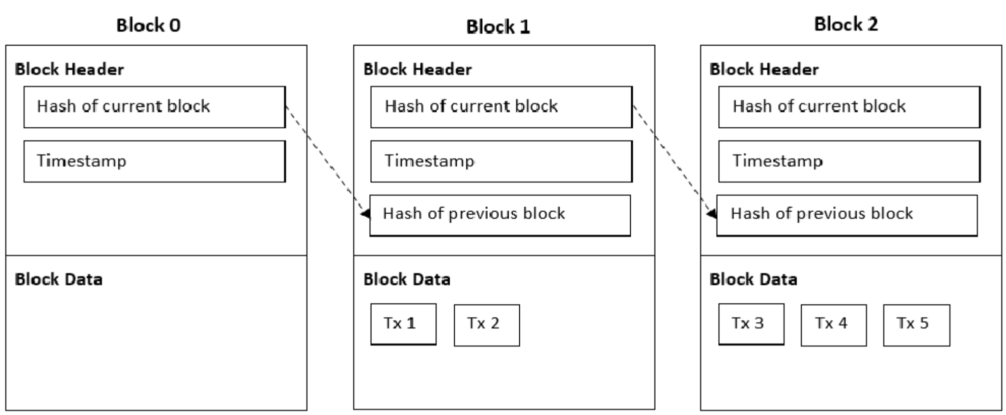

Figure 3: Structure of blockchain

Blockchain is a chronological log of blocks that are interlinked by block hash. Each block consists of a block header and block data. The Block header contains hashes of the current and previous blocks, and block data contains a list of transactions in chronological order, as shown in Figure 3. We further discuss some features of our proposed architecture below.

1) Registration and enrollment

All users must register to the blockchain network and enroll in an organization. Fabric certificate authority (CA) admin proves the user's identity using public-private key pair and issues a user ID. Membership service providers (MSPs) link the user's ID to the membership of an organization and define the user's role and permissions inside the organization.

2) Data access

Medical images are stored in the onsite PACS, and exam IDs are stored in the blockchain. Teleradiologists can request access through their user application, and a link to view the images will be provided once peers in the blockchain network verify the request. Records of access requests and data accesses are added to a block as a hash, and the ledger gets updated with the new block.

3) Critical-result notification

Teleradiologists can also notify the provider and the care team of critical findings and request a call with the physician through the user application. Smart contracts can also be implemented in a way that pre-arranged keywords in the radiology report invoke them to send an alert to the patients' provider.

B. Prototype

We developed a user application based on our proposed architecture, called "TeleRad." There are four roles in the system; Admin, Care provider, Teleradiologist, and Care team member, and each role is granted with different privileges. User registration is required to use the application. Once the admin approves their registration with assigned roles, users can view patient data or make requests. Screenshots are provided below to demonstrate the application flow among each view.

1) Admin view

Fig. 4 shows the admin view with a new registration request and how the admin adds the new user. Once the admin approves the new registration with an assigned role, the user can view or request patient data through the application.

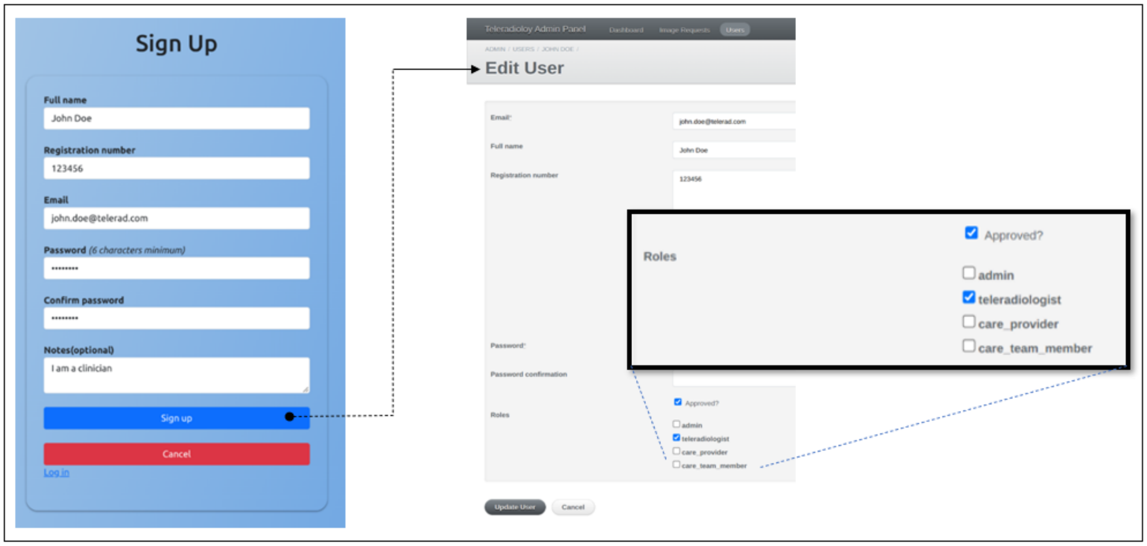

Figure 4: Prototype Screenshot- Admin view

2) *Teleradiologist view*

Fig. 5 presents the application flow when teleradiologists request images or critical connections. Radiologists can request images by submitting an image request and are instantly provided with a link to access the requested images. In addition, radiologists can check the Critical Notification box to communicate critical findings or the need for a critical connection with the patient's care team. When the box is checked, the patient's physician and care team will immediately get a notification on their user application.

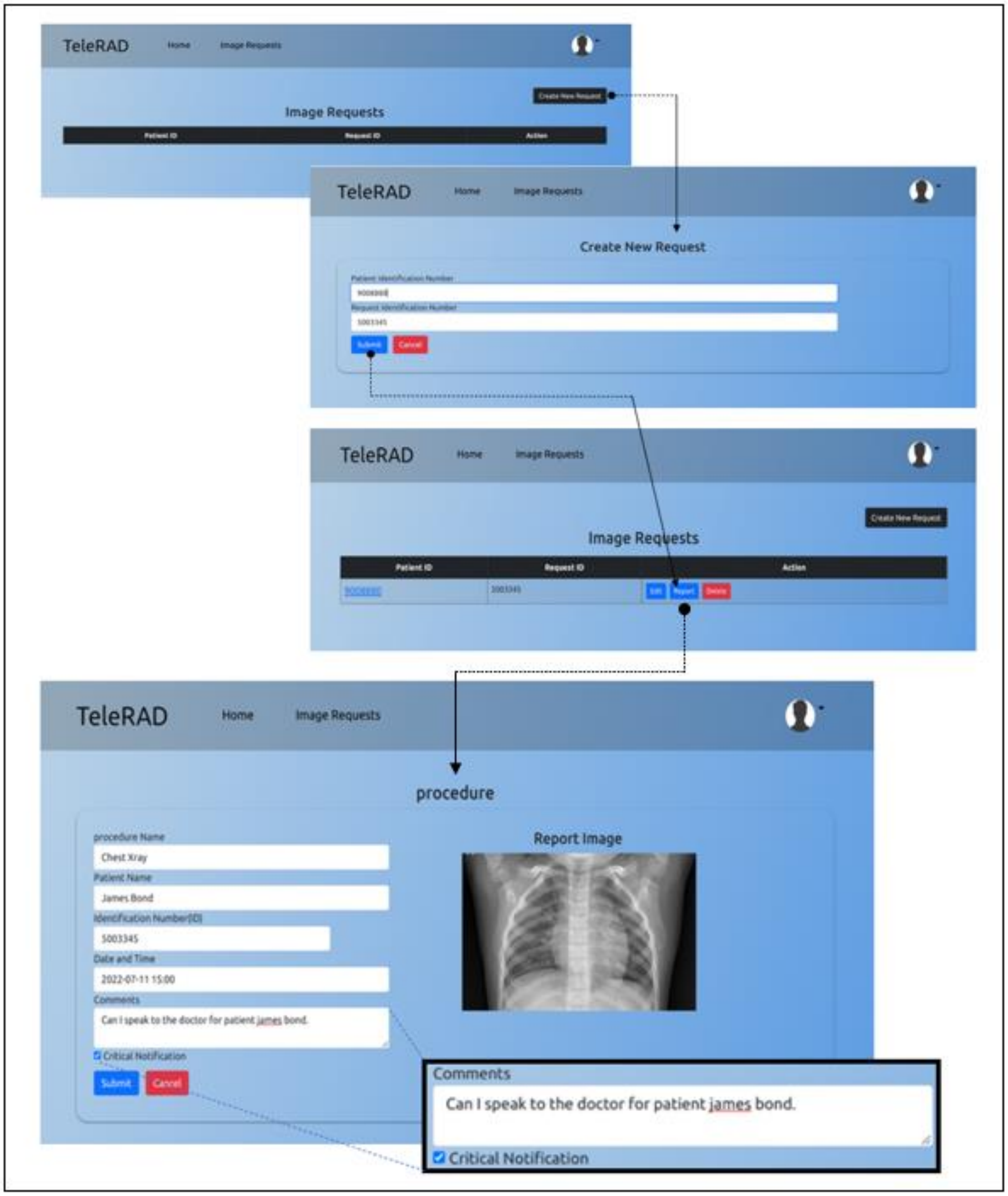

Figure 5: Prototype screenshot- Teleradiologist view

3) Critical-result notifications

Fig. 6 demonstrates the application flow regarding critical notifications. The Critical tab on the physician and the care team members' home screen is in green by default. Upon receiving new critical notifications, the tab is highlighted red with numbers of new critical notifications inside a bracket. When clicking on the tab, they can check the detail of the critical notifications. Once resolved, the Critical tab turns back to green.

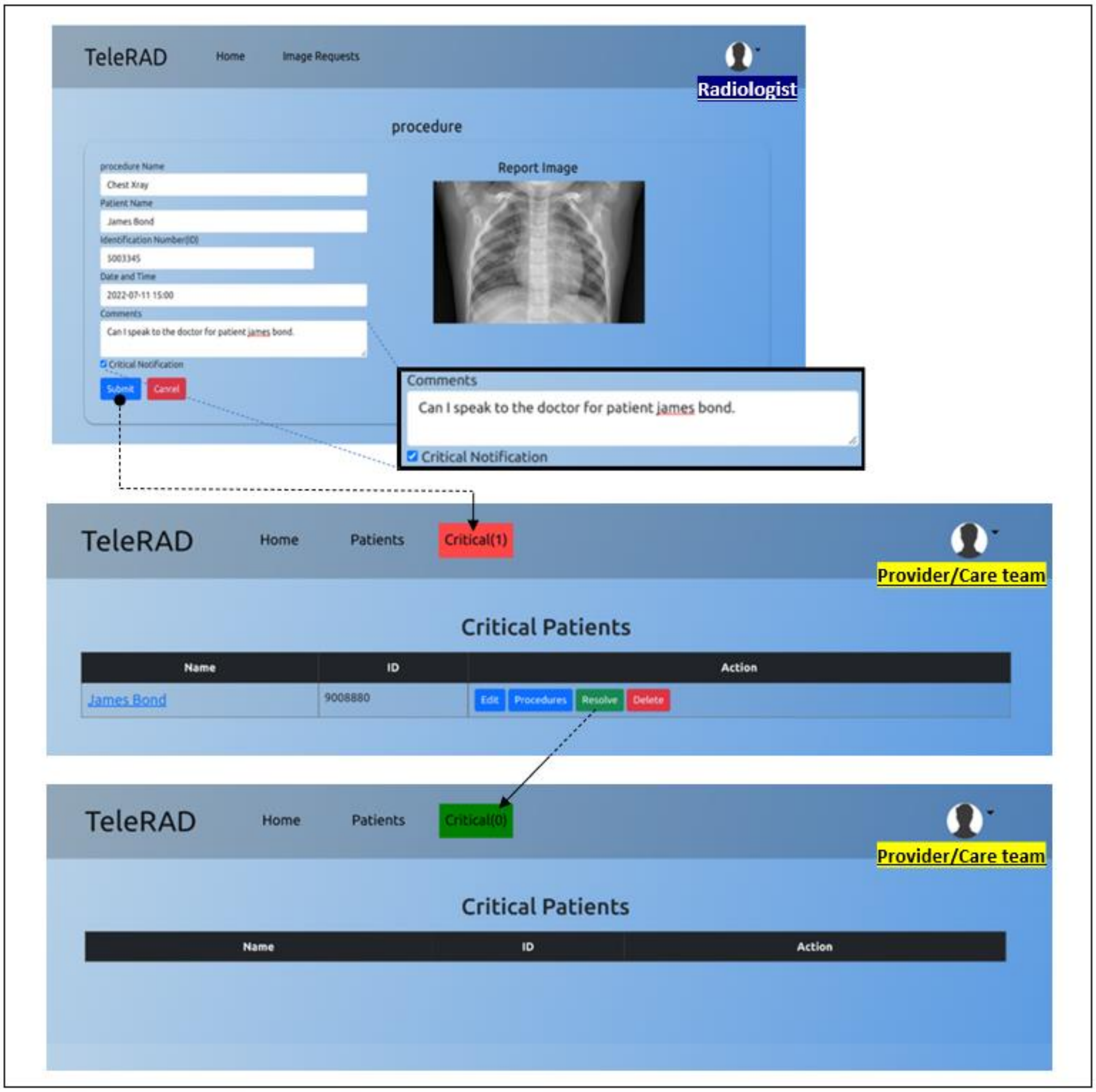

Figure 6: Prototype screenshot- Critical notifications

CHAPTER V.

DISCUSSION | LIMITATIONS

In section III, we demonstrated the current teleradiology workflow with its pain points where delays occur in processing radiologists' requests for images or critical connections. We believe that our blockchain-based model can be a potential solution to address these issues by automating the processes. Automating the process eliminates the need for intermediary communications to significantly reduce the number of steps and process time, optimizing the workflow. Process automation also benefits the organization by cutting down operational costs from eliminating the need for intermediary personnel.

A. Minimized number of steps in the process

With our application, radiologists can request images or critical connections through a user application. After the authentication and validation process, radiologists will instantly receive a link to view the requested images. Also, critical connect requests will be sent directly to the care team without having to go through intermediary personnel. A comparison of the two systems is summarized in Figure 7.

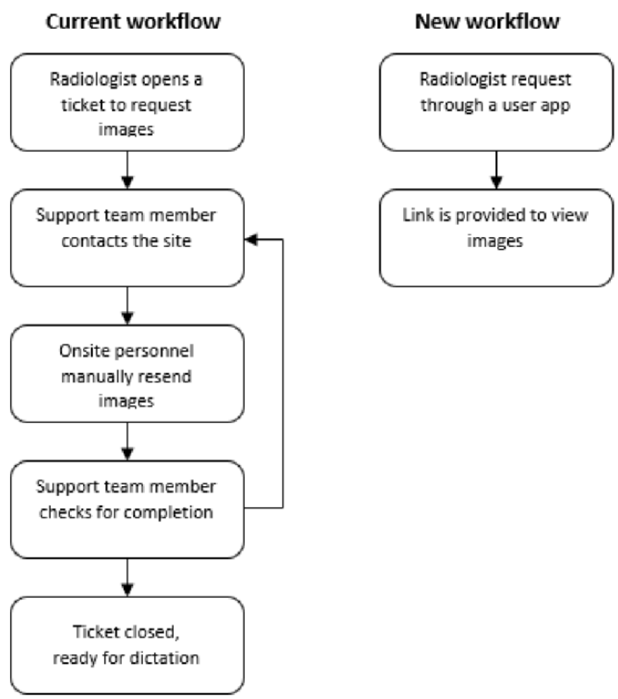

Figure 7: Workflow comparison

B. *Reduced process time*

In the current system, delays occur as resolving radiologists' requests requires intermediary personnel to communicate manually through phone calls and voicemails. However, our prototype eliminates possible delays by automating the process. Our application allows radiologists to get a link to the requested images instantly. In addition, the onsite care team will be immediately notified of critical findings and critical call requests, as mentioned in Chapter IV in Fig 6. The average process time for these automated processes is around 30 milliseconds, as shown in Fig. 8 below, significantly improving the current process time of 15-30 minutes. This improvement will optimize workflow on teleradiologists and clinical sides by minimizing interruptions and benefit patients with a much faster turnaround time.

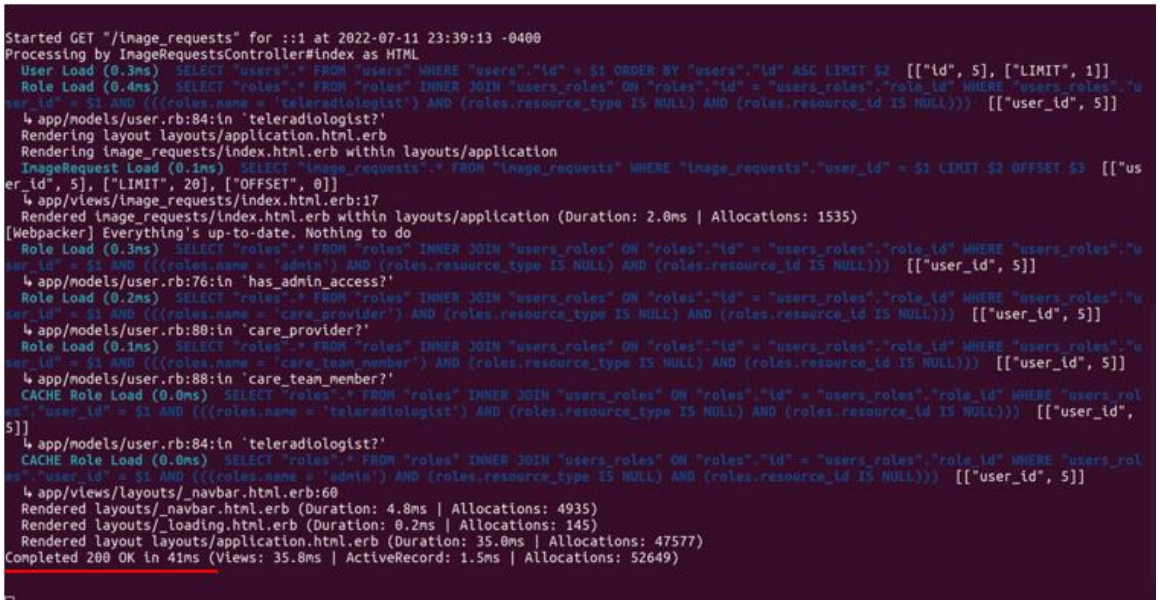

Figure 8: Prototype Screenshot- Image request Process time

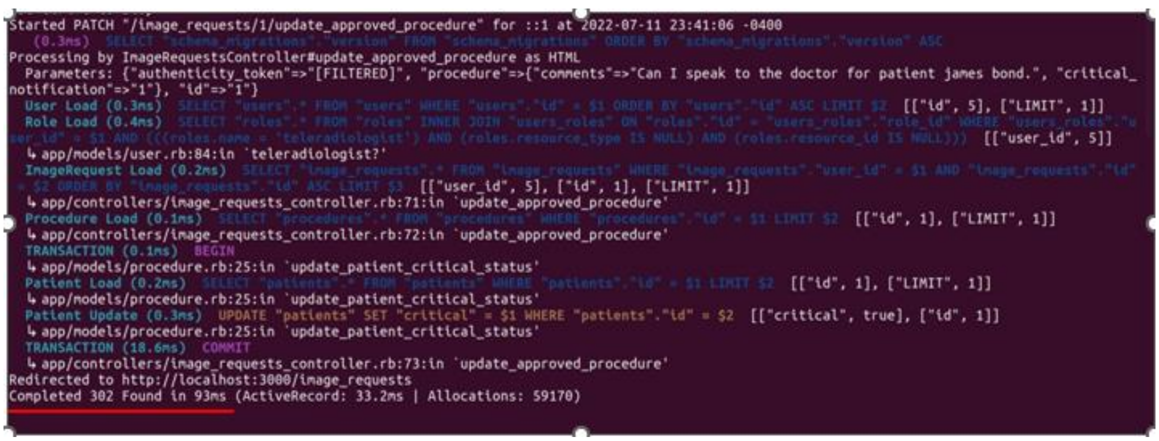

Figure 9: Prototype Screenshot- Critical notification Process time

C. *Enhanced efficiency in managing access data*

In our proposed architecture, access requests and access logs are recorded in a block, as shown in Fig. 9. Each new block is added to the blockchain in a timely order. With its distributed and tamper-resistant nature, blockchain offers great advantages of transparency, trust, security, scalability, and data traceability in managing access control data. Thus, we can prevent single points of failure, and malicious attempts to tamper with the access data can be easily detected [21], [22].

Figure 10: Prototype Screenshot- Hyperledger Approval Log

D. Limitations

One of the limitations of our proposed architecture is that we did not include patients as an entity as we developed the model emphasizing optimizing the workflow. However, patients can be added to the network to view their medical images or request to share images with their physicians to allow them better access to their images. Once registered to the network, patients can request to view or share images. They do not need to fill out Release of Information (ROI) forms every time they request images and sharing images with their physicians will be more efficient than sharing them through hard copies (e.g., CD or DVD). Furthermore, there are challenges to implementing new technology in healthcare due to initial expenses, organizational and cultural resistance to change, and lack of policy and governance structures. The modular architecture of our proposed model using the originating site's PACS infrastructure facilitates the implementation and aids regulatory compliance. However, further research on governance and HIPAA compliance is required to optimize the adoption of the new application [23], [24].

CHAPTER VI.

CONCLUSION

In this thesis, we proposed a blockchain-based medical image sharing and critical-result notification to optimize teleradiology workflow and reduce radiology report turnaround time. First, we discussed challenges in the current workflow: prolonged turnaround time caused by image unavailability and delayed critical-result communication and how blockchain technology can be a potential solution to address these issues. Then, we presented a detailed architectural framework and a prototype built based on the framework. Our prototype can automate to simplify the process and reduce process time significantly. For future work, we aim to improve our prototype through user testing. Furthermore, we will work on enhancing the functionality by implementing smart contracts to trigger critical notifications with key diagnostic terms. In addition, with blockchain being a new technology in healthcare, further research on governance and HIPAA compliance is required for successful implementation.

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