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Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE)

Design and Prototyping of the Web-based Teleradiology System. Case Study of Rwandan Hospitals.

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A Dissertation Submitted to the Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE), University of Rwanda as partial fulfilment of the requirements for the Master's Degree in Biomedical Engineering.

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ABSTRACT

The shortage of specialists who possess the expertise to accurately read and interpret CT-scan, MRI, and some X-ray images poses a significant challenge in the current healthcare system in Rwanda. This shortage results in an increased workload for the designated specialists, which can lead to delayed diagnosis and treatment, decreased quality of care, and increased costs to both patients and healthcare providers. Teleradiology is a solution that can help to address this challenge. Teleradiology allows radiologists to read and interpret medical images from remote locations including but not limited to district hospitals. This research study describes the design and implementation of a web based teleradiology system prototype designed for Rwandan hospitals, ranging from district to referral levels. The system was developed using the MERN stack, a popular choice for developing web applications and it is designed to be scalable, safe, and user-friendly. The project progresses through several phases, including literature review, needs assessment, and the creation of a web application prototype. This study helps to advance teleradiology in Rwanda by increasing access to specialized expertise, enhancing diagnostic accuracy and efficiency, and encouraging collaborative healthcare practices.

Keywords: Teleradiology; Medical imaging; MERN; Access to healthcare

DECLARATION

I, UN Francois RUDASINGWA declare that this dissertation entitled “**Design and Prototyping of the Web-based Teleradiology System. Case Study of Rwandan Hospitals**” is my original work based on research and prototype and has not been submitted for any other degree or professional qualification.

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CERTIFICATE

This is to certify that the project entitled “**Design and Prototyping of the Web-based Teleradiology System. Case Study of Rwandan Hospitals**” is a record of original work done by **UN Francois RUDASINGWA** (Ref. No. **215043302**), a MSc. Degree student in Biomedical Engineering.

This work has been submitted under the guidance of **Prof. Celestin TWIZERE** and **Prof. Yunjie Tong**.

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LIST OF ACRONYMS

S/N	Acronym	Full Word
1	API	Application Programming Interface
2	CEBE	Center of Excellence in Biomedical and e-Health
3	CHUB	University Teaching Hospital of Butare
4	CHUK	University Teaching Hospital of Kigali
5	CST	College of Science and Technology
6	CT	Computed Tomography
7	DICOM	Digital Imaging and Communications in Medicine
8	GIT	Global Information Tracker
9	ICD	International Classification of Diseases
10	IP	Internet Protocol
11	KFH	King Faisal Hospital
12	L2TH	Level 2 Teaching Hospital
13	MERN	MongoDB, Express, React and Nodejs
14	MRI	Magnetic Resonance Imaging
15	PACS	Picture Archiving and Communication System
16	RMH	Rwanda Military Hospital
17	UR	The University of Rwanda

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Chapter 1: INTRODUCTION

1.1 Observation

The shortage of specialists who possess the expertise to accurately read and interpret CT-scan and MRI images and some X-ray images poses a significant challenge in the current healthcare system. According to Ishimwe Patrick, a Medical Doctor, the limited number of qualified professionals, results in an increased workload for the designated specialist at the referral hospital, leaving them with little time to accurately assess these important medical images. As a result, **the timing or quality of the patients' diagnosis and treatment is compromised**. At the same time, there might be available specialists at Kanombe military hospital, CHUK or King Faisal Hospital (KFH) hospitals or any other place who are not overloaded. Addressing this issue is crucial to ensure timely and accurate diagnosis for patients requiring these images interpretation and to improve the quality service.

1.2 Problem Statement

The limited availability of specialists skilled in accurately interpreting CT-scan, MRI, and certain X-ray images presents a substantial hurdle within the healthcare system. This scarcity places an excessive burden on designated specialists, potentially causing delays in diagnosis and treatment. Overworked specialists may struggle to allocate sufficient time to thoroughly evaluate medical images, compromising patient outcomes and the overall quality of care provided. **Decreased quality of care:** When specialists are overworked, they may make mistakes. This can lead to misdiagnosis, which can have serious consequences for patients and the healthcare system in general. **Increased costs:** The cost of healthcare can increase when there is a shortage of specialists. This is because hospitals may have to pay higher salaries to attract and retain qualified professionals as well as patient travels. Developing a web based teleradiology system that links local radiologists to specialists will help in reduction of these challenges.

1.3 Research Questions (Hypotheses)

The following 3 questions are the baselines which guided this study.

- **Accuracy & Efficiency:** Can a web teleradiology system improve Rwandan hospital diagnoses (CT, MRI, X-ray)?
- **Scalability & Usability:** Can the MERN stack build a scalable and user-friendly teleradiology system for all Rwandan hospitals?
- **Security and Privacy:** How secure is the web-based teleradiology system in protecting sensitive patient data during image transfer and storage within the Rwandan context?

1.4 Aims and Objectives

1.4.1 General objective

To design and prototype a teleradiology web application that will improve the quality of care for patients in Rwandan hospitals.

1.4.2 Specific objectives

- Identify the needs of teleradiology in Rwandan hospitals.
- Design system architecture of a web app teleradiology system that meets the needs.
- Develop a web app prototype for the teleradiology system that connects hospitals.
- Testing the web app teleradiology prototype.

1.5 Study Scope

The scope of this research project encompasses the design and prototyping of a web based teleradiology application that can connect referring hospitals and referral hospitals in Rwanda.

1.6 Significance of the study

This study provides a promising solution to the challenges associated with the scarcity of specialists in medical imaging interpretation, with potential benefits including improved patient outcomes, higher quality of care, and cost savings within the healthcare system.

1.7 Organization

Chapter one gives the introduction, chapter two discusses the literature reviews, chapter three discusses about the methodology used, chapter four talks about testing and result discussions of research findings and finally chapter five discusses conclusions and recommendations from the research study.

Chapter 2: LITERATURE REVIEW

2.1 Telehealth

The use of communications technologies to provide and support health care at a distance [1]. Telehealth has become a valuable tool thanks to combined advances in communications, computer science, informatics, and medical technologies that allow a remote diagnostic or a treatment plan.

2.2 How can telehealth technologies improve medical care?

Teleconsultations allow a physician in a remote area to receive advice from a specialist at a distant location about special or complex patient conditions. Such consultations can be as simple as a phone call. Increasingly, they involve sophisticated sharing of medical information such as CT, MRI or ultrasound scans. These images can be taken by the local physician, incorporated into an electronic medical record and sent to the specialist for diagnosis and treatment recommendations [1].

Teleradiology refers to the practice of a radiologist interpreting medical images while not physically present in the location where the images are generated.

2.3 Telemedicine: Good or Bad and for Whom?

The American Telemedicine Association defined telemedicine in 2014 as “the use of medical information exchanged from one site to another via electronic communication to improve a patient’s health status”. It is largely regarded as a resource with the potential to transform access to care. It is up to each telemedicine provider's facilities to deliver what remote health consultation may provide, which can include computer-tomography, magnetic resonance imaging, and ultrasound, otoscopy, blood sugar monitoring, as well as blood pressure and oximetry, are all provided by various electronic programs. However diagnostic or therapeutic services provided through such sites must meet general and specialty specific standards [2].

Telemedicine provides a feasible way for patients/clients to access health practitioners (nurses or physicians) at a distance using electronic informatics and electronic communications technology.

It provides a rapid assessment of a patient's health situation, allowing for fast intervention in an acute coronary syndrome or stroke, as well as timely referral to a tertiary care hospital. For those patients well known to their doctors, In a win-win situation, this means less time spent by the patient, a shorter visit for the physician, and more time for him to do other things.

Additional Benefits of telemedicine

a. Comfort and Convenience

Telemedicine eliminates the need for individuals to go to a physical doctor's office or clinic, find parking, traverse waiting rooms, or even take time off work or arrange childcare, depending on their schedule. Virtual appointments are convenient, making it easier to accommodate busy schedules.

b. Control of Infectious Illness

To help prevent the spread of COVID-19, flu and other infectious diseases, doctors can use telehealth appointments to prescreen patients for possible infectious disease. It also saves sick people from having to come into the office. Less exposure to other people's germs helps everyone, especially those who are chronically ill, pregnant, elderly or immunocompromised [3].

However, there is some concern about telemedicine's ability to give data that only a face-to-face contact can provide. "No touch" medicine can be dangerous, deceptive, and result in incorrect diagnoses and therapies, with unintended consequences for all parties involved in patients' care. Considering the facts stated above, it is evident that some symptoms, indications, and diagnoses can be delivered via telemedicine while others cannot. It is essential that the health care provider accurately determines when a "hands-on" medical visit or referral to another practitioner is required for a proper diagnosis and treatment.

2.4 Internet-based medical image viewing system

Electronic medical image viewers combined with picture archival and communication systems have become a common part of how hospitals manage their images. Typically, these electronic viewers are platform-dependent and are designed to make use of images stored on a workstation or local area network [4]. Teleradiology can improve imaging efficiency and reduce regional and temporal disparities in imaging care. Technological limits and legal barriers impede the best practice of teleradiology, and future attention to these concerns may assist ensure more patient access to high-quality imaging across the United States [5].

2.5 Different Telemedicine systems

Telemonitoring. The patient communicates with the healthcare team by some sort of remote technology (cell phone, mobile application, or computer). Patients receive automated feedback and/or a response from the medical team after finishing the examination [6].

Telehealth visits. The patient enters a "virtual exam room," where he or she and the practitioner engage in a clinical engagement.

2.6 Telemedicine for Orthopedic Consultations

Orthopedic is a branch of medicine concerned with the correction or prevention of deformities, disorders, or injuries of the skeleton and associated structures (such as tendons and ligaments). During the COVID-19 pandemic, orthopedic associations called for telemedicine to prevent disease transmission while still delivering care to orthopedic patients which includes American Academy of Orthopedic Surgeons, British, Orthopaedic Association, and Australian Orthopaedic Association [7].

The organization of telemedicine visits for patients as well as admission schedules are critical factors in optimizing patient flow and timetables, accommodating more patients, and lowering patient wait time. These are in addition to the resource/personnel needs such as hardware, software, network connectivity, and patient/provider characteristics, as well as professional expectations.

2.7 Telemedicine for vital signs monitoring

With the Covid-19 outbreak, one of the crucial challenges of telemedicine is the real-time application monitoring for the vital sign. The commercial platform is, by far, not suitable for real-time applications. The alternative is to design a web-based application exploiting Web Socket [8]. The six vital-sign parameters:

- Body temperature: The normal body temperature for adults is 98.6 degrees Fahrenheit (37 degrees Celsius). A fever is a temporary increase in body temperature that is often caused by an infection.
- Pulse rate: The pulse rate is the number of times the heart beats per minute. The normal pulse rate for adults at rest is 60 to 100 beats per minute.
- Respiratory rate: The respiratory is the frequency of breaths taken per minute. The normal respiratory rate for adults at rest is 12 to 20 breaths per minute.

- Blood pressure: Blood pressure is the force of blood pushing against the walls of the arteries. The normal blood pressure for adults is less than 120/80 mmHg.
- Oxygen saturation: Oxygen saturation is the percentage of oxygen in the blood. The normal oxygen saturation for adults is 95 to 100%.
- Pain: Pain is a subjective experience that can be caused by a variety of factors, including injury, illness, and surgery. Pain can be measured using a variety of scales, such as the visual analog scale (VAS) or the numeric rating scale (NRS).

Plethysmography is a non-invasive technique that can be used to measure blood volume, blood flow, and oxygen saturation in various parts of the body.

2.8 Telemedicine in Africa

Women in Africa have inadequate access to maternal health care, despite the fact that it is a critical factor of maternal mortality and morbidity and, 830 women die every day from preventable causes owing to inadequate maternity care [9]. Almost 99% of deaths occur in low-income countries, with half occurring in Sub-Saharan Africa, where maternal mortality is extremely high. This is due to barriers to maternity care, including transportation and dispensary proximity as main factors. According to a 2021 survey, one in every four pregnant women did not have access to prenatal care. The majority of these women lived in Chad (37%), followed by Nigeria (38%).

Telemedicine has been adopted in some African countries but ignored in others due to a lack of finance or political support. Countries such as Mali, Nigeria and Senegal, for example, have welcomed the practice of telemedicine, since many programs aimed at transforming healthcare in Africa are currently underway.

With the assistance of the Geneva government, a project called "Keneya Blown" was launched in 2001 with the goal of providing internet-based linkages to Mali's provincial and national healthcare institutions. Remote examinations of patients in the North and South of Mali are also possible through the Mali project. To continue, several mobile health (mHealth) programs in Tanzania, such as Healthy Pregnancy, Healthy Baby (HPHB), and MomConnect in South Africa, are examples of effective innovations to improve maternal care in Africa.

2.9 Telemedicine in Rwanda

Rwanda, health information technology is a rapidly growing business with numerous stakeholders, including the national government, multiple NGOs groups, and the corporate sector. The objective is to incorporate technology into the increasing health-care system.

To build on Rwanda's will in healthcare and technology, and to accelerate progress toward the country's long-term development goals, in March 2020 the government entered a ten-year partnership with UK-based remote consultations provider Babylon Health [10]. which established Babyl with their mission is “Babyl believes it is possible to put an accessible and affordable health care service in the hands of every person on earth.

How? By combining the ever-growing computing power of machines with the best medical expertise of humans to create a comprehensive, immediate and personalized health service and making it universally available.” As of now more than **2.9 million** consultations were performed. These services include High Quality GP & Nurse Consultations, Laboratory Test Results over the Phone, Prescriptions Filled Nationwide, referring if needed.

As of 2011, the following six health technologies were being implemented in Rwanda to respond to the health-care needs of the population and to improve management of the health system in which the first two were operational by the time were operative [11].

- **TRACNet:** monthly monitoring of infectious diseases including HIV/AIDS, tuberculosis and malaria.
- **CAMERWA:** a drugs and medical supply management system handled by the national pharmaceutical company.
- **Open MRS:** an open medical records system that tracks patient-level data.
- **Telemedicine:** ICT used to deliver health services and health-care information and education to geographically separated parties.
- **HMIS:** health management information systems.
- **e-learning for nurses.**

This resulted in electronic data of HIV/AIDS patients, enabling for the retrieval of up-to-date information regardless of which health facility the patients attended. This is critical for patient follow-up, multidrug-resistant tuberculosis surveillance, and so on.

Challenges

- The need for training for the health-care professionals on different systems (softwares)
- A paper-based and electronic system has existed since 1997 to report the activity of health-care facilities, but Microsoft Access was not fully compatible with TRACNet.

2.10 Teleradiology on patients' diagnosis and treatment

High-quality diagnostic imaging can improve diagnostic accuracy and help guide medical decision-making and care, but there are several limitations for radiology in resource-limited settings and availability of specialists. Diagnostic imaging and teleradiology have both financial and logistical implications, so evidence of impact is crucial, that reduces unnecessary costs. In developing countries like Rwanda with resource-constrained situations, computed radiography and teleradiology shows great clinical value, with the potential to improve patient outcomes through improved diagnosis and treatment strategies [12].

2.11 The International Classification of Diseases (ICD)

The International Classification of Diseases (ICD) or International Statistical Classification of Diseases and Related Health Problems constitutes a diagnostic classification standard and tool for all health disorders including epidemiological, clinical, research and health management issues. It is published and overseen by the World Health Organization (WHO) and is designed to improve the comparability of statistical data internationally between different locations and within the same location across different time periods [13].

The latest version, the ICD-11 was released in June 2018, endorsed by the 72nd World Health Assembly in May 2019 and was put into effect in January 2022. It encompasses more than 100,000 medical diagnostic index terms and an implementation package including transition tables and a coding tool, as well as other services and utilities. Changes from ICD-10 to ICD-11 include the introduction of new diagnoses, the refinement of diagnostic criteria of existing diagnoses, and notable steps in the direction of dimensionality for some diagnoses.

2.12 Medical Image File Formats and Digital Image Conversion

Medical image file formats make a confusing aspect to young researchers who start work with medical images. Medical image format conversion is still a tedious task due to the different structure of files. Digital image conversion from the medical image is an important pre-processing step to the process and visualizes the data [14]. The medical image format is divided into Metadata (technical, descriptive and administrative) and Image data

$$\text{Image size} = \text{size of metadata} + \text{no. of rows} \times \text{no. of columns} \times \text{bits per pixel}$$

Table 2-1: General characteristics of famous medical image formats

Format	Year	Extension	Header Length (in Bytes)	Files per Scan	Produced by
Analyze 7.5	1980	.img/.hdr	348 bytes	Two	PET
NIFTI-1	2000	.nii	352 bytes	More number of Slices	PET
MINC 2.0	1992	.mnc	Highly standardized and extensible	One	Diffusion MRI (dMRI)
DICOM	1993	.dcm	128 bytes File Preamble + 4 bytes DICOM prefix	More number of Slices	CT, MRI, X-ray, fluoroscopy, angiography, mammography, PET, SPECT, Endoscopy, microscopy

2.13 Obstacles during Teleradiology Network Development

Developing a teleradiology network has challenges such as high initial costs, which may discourage investment in critical technologies. Inadequate inter-institutional transmission speeds impede the timely interchange of medical pictures among facilities. Furthermore, the diversity of technical systems across sites creates interoperability issues. Addressing these challenges needs strategic planning, infrastructure investment, and stakeholder participation to ensure seamless communication within the teleradiology network [15].

2.14 MERN Stack for Web Development

Web development refers to the process of building, constructing, and maintaining websites. The MERN stack includes four core technologies: MongoDB, Express.JS, React.JS, and Node.JS, replacing standard web development methods such as HTML, CSS, and JavaScript. Clearly, it is a JavaScript stack that enables easy development and speedier deployment. This work's key contribution is an in-depth analysis of each technology component on the stack [16].

MERN is a web development stack that enables the creation of both web and mobile applications. React Native is a popular hybrid mobile development framework that supports both Android and iOS, built on JavaScript and React JS.

React Native can be used to develop the mobile app's UI, and Node JS for the backend. Because JavaScript is utilized throughout the stack, developers do not need to learn and switch gears to work with a new technology, resulting in a short learning curve. The entire stack is relatively simple to master and ideal for novices. It's frequently used in the online industry.

Express: It is the backbone of Node.js, released as free and open-source software under MIT license. Built web applications and APIs. It is called a standard de facto server Node.js frame [16].

MongoDB: MongoDB is a documentation site that makes it easier to construct and measure applications. If the app saves any data (user profiles, content, comments, uploads, events, etc.)

2.15 Data Standards in Tele-radiology

Data standards play an important role to provide interoperability among different systems. As other applications of telemedicine, tele-radiology needs these standards to work properly [17]. In healthcare, the term "data standards" encompasses methods, protocols, terminologies, and specifications for the collection, exchange, storage, and retrieval of information associated with health care applications, such as medical records, medications, radiological images, payment and reimbursement, medical devices and monitoring systems, and administrative processes.

2.15.1 Data interchange standards

- **DICOM:** Digital Imaging and Communications in Medicine (DICOM) is the most important standard for transmission of digital images and diagnostic and therapeutic information. DICOM was developed by the cooperation of the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) in 1983 [18].
- **JPEG 2000 Interactive Protocol (JPIP):** JPIP is a client/server standard image streaming protocol and based on the JPEG 2000 standard. JPEG2000 is an ISO/IEC standard and facilitates image streaming.

2.15.2 Document standards

- The DICOM structured report (DICOM SR)
- Health Level 7 (HL7) Clinical Document Architecture (CDA)

2.16 Password and Salt Combination Scheme to Improve Hash Algorithm Security

Hashes are vital in system security because they ensure data integrity. It remains secure, with access permissions managed by those who are entitled to them. The rising power of hash algorithms is accomplished through a variety of approaches, one of which employs salting techniques. Salt is typically added as a prefix or postfix to plaintext before hashing. However, simply adding salt as a prefix or postfix will not suffice. There are numerous approaches to determining the plaintext from the generated cipher text [19].

Hash is an algorithm that converts a string into a collection of random characters. It is also known as a one-way function or one-way encryption because it can only encrypt data and does not have a decryption key. It operates by receiving input strings of arbitrary length and transforming them into a string of fixed length, which is called the hash value.

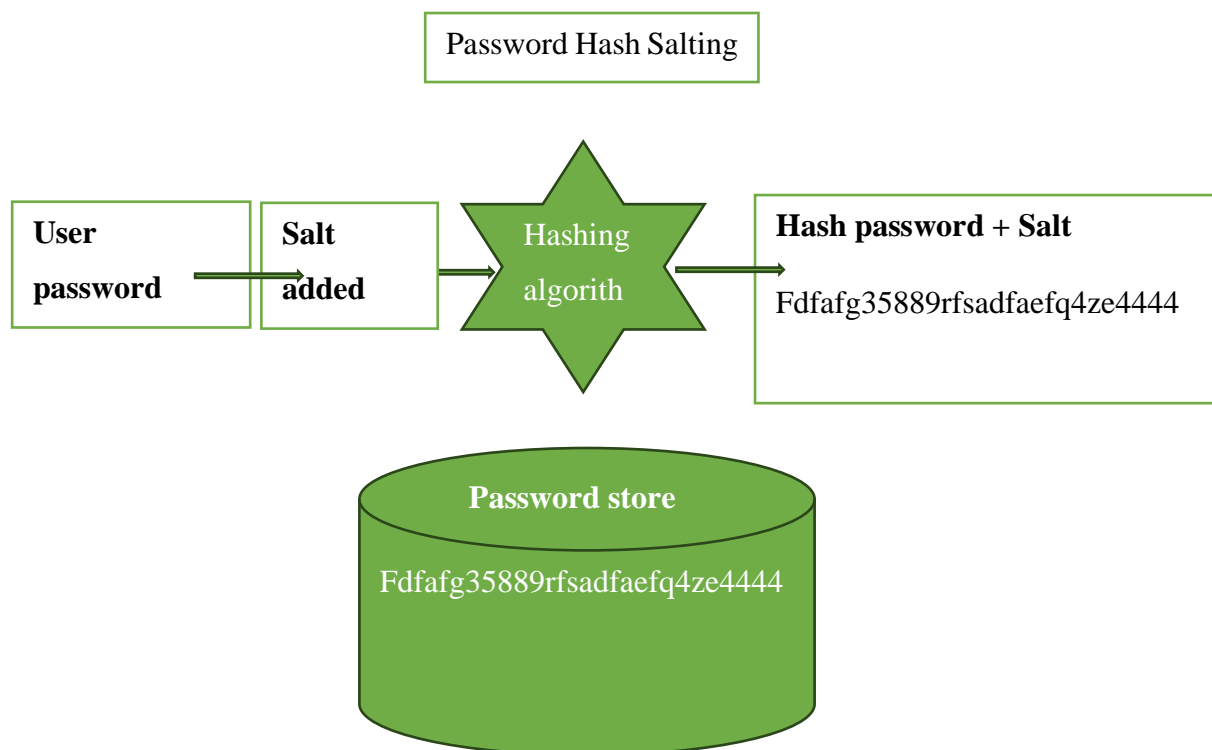


Figure 2-1: Hashing and salting

Chapter 3: METHODOLOGY

In this research both field and systematic approaches will be used, thereby conducting a thorough examination of the available literature on teleradiology technologies, their application, and best practices in healthcare settings. Determining the limitations and benefits of teleradiology in the context of Rwandan hospitals. Analyze the current state of Rwanda's teleradiology systems and identify holes that must be filled. Interviews and questionnaires with the practitioners (radiologists and other healthcare professionals).

3.1 Research process

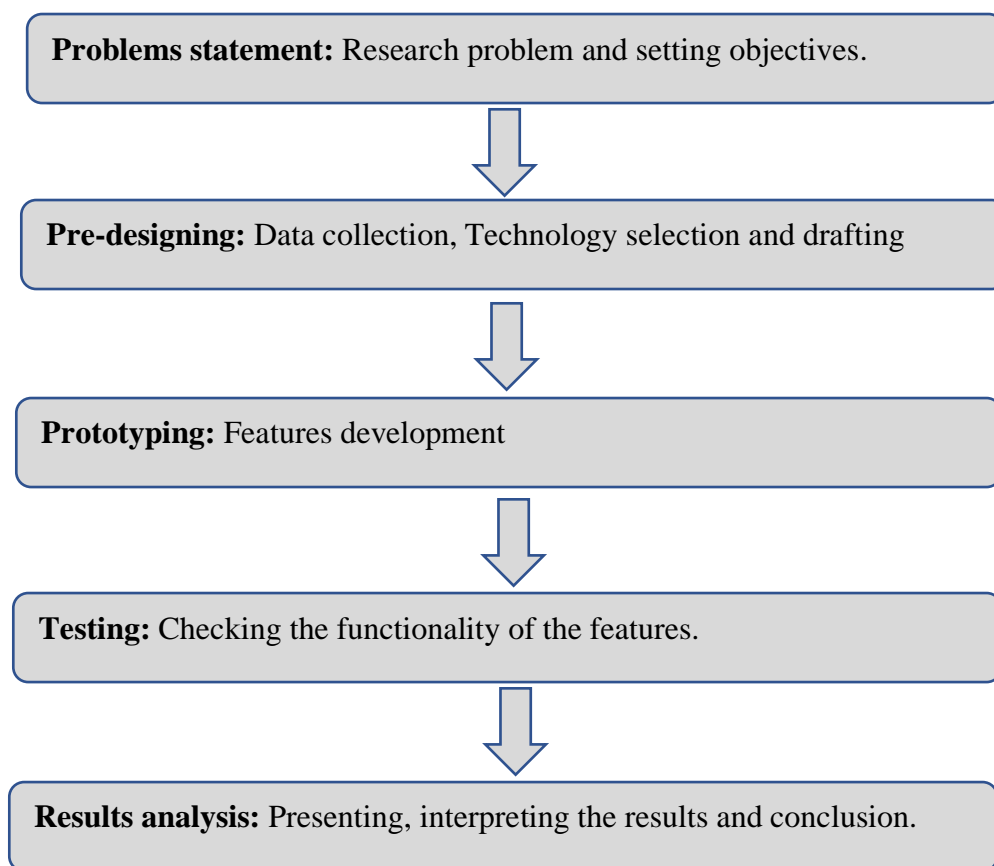


Figure 3-1: Web App Teleradiology Design Development flowchart

3.2 Data collection

The data were collected to assess the current radiology landscape in Rwanda (2024), this study collected data on three key areas: the need for specialist interpretation of medical images (CT, MRI, X-ray), the number of radiologists working in Rwandan hospitals, and imaging modalities availability and radiologists' current workload.

3.2.1 Data collection method

To comprehensively assess Rwanda's radiology landscape in 2024, a mixed-methods approach was employed for data collection. Primary method, data was gathered through questionnaires distributed via Google Forms and phone call interviews. This allowed for direct interaction with key stakeholders, including radiologists, Ministry of Health (MOH) staff, and hospital data managers. Selection of participants was purposive, focusing solely on individuals with relevant expertise in the field. Following introductions and outlining the research objectives, informed consent was obtained using an ethical clearance document (refer to Appendix 3) before proceeding with the data collection process. Secondary data collection was done through literature reviews.

The collected data helped to reveal a key deficiency in Rwanda's healthcare system. This gap underscored the importance of creating and implementing a teleradiology system to solve the problems outlined.

3.2.2 Data summary

Table 3-1: Imaging modalities in Rwanda and near future plans from MOH

Imaging Modalities in Rwanda			
Modality	QTY	Location	Near future plan
MRI machines	4	<ul style="list-style-type: none"> - KFH - Medheal - Legacy - Gisenyi 	<ul style="list-style-type: none"> - RMH - CHUK - CHUB with MRI
CT scan machines	13	<ul style="list-style-type: none"> - KFH - CHUK: 2 - CHUB - RMH: 2 - Kibungo L2TH - Kibuye - Butaro L2TH - Legacy - Baho - WIWO 	<ul style="list-style-type: none"> - Ruhengeri with a CT - RMH with PET CT

		- Polyclinique (La Medicale)	
X-ray and Ultrasound machines	Many	All district hospitals	

The analysis of the data revealed a critical shortage of Rwandan radiologists. As reported by Dr. Jean Jacques NSHIZIRUNGU, radiologist and Dr. Patrick NIYONGABO, Junior Consultant Radiologists at KFH, there are currently only 13 practicing radiologists in the country, with some additional support provided by foreign radiologists affiliated with NGOs and private healthcare providers. These interviews further emphasized the urgent need for a teleradiology system. Such a system would not only eliminate the insecure practice of transferring medical images (CT, MRI, X-ray) via WhatsApp and email but would also create a platform for enhanced collaboration among healthcare professionals, facilitating activities such as tumor board: a group of doctors and other health care providers who are experts in cancer care and meet regularly to discuss complex cancer patient cases and share knowledge, as well providing references, guides and teaching material for students.

3.3 Research Design Method

3.3.1 Pre-Designing of subsystem

3.3.1.1 Technology selection: MERN Stack with TypeScript and Nest JS

Frontend:

- **React.ts(x):** This is a JavaScript library for building user interfaces (UI). React.ts(x) would be used to create the interactive web interface for the teleradiology application. This includes features like secure login pages, image viewers for radiologists to analyze medical scans, and report creation sections among others.
- **Axios:** This is a popular HTTP client library for JavaScript (both frontend and backend with Node.js). It simplifies making asynchronous HTTP requests to backend APIs from the React frontend. promise-based handling, or standardized communication across multiple APIs (Application Programming Interface).

- **Node.js:** This is a JavaScript runtime environment that allows to run JavaScript code outside of a web browser. Node.js acts as the foundation for the entire MERN stack, this allows it to build a server-side application that interacts with the database and provides functionality to the React.ts(x) frontend.

Backend:

- **Express.js:** This is a popular web framework for Node.js that simplifies building web applications. Express.js is used to handle incoming requests from users (radiologists, referring physicians and admins), process data, and interact with the MongoDB database. In the context of this app, Express.js handles functionalities such as user authentication, image uploads and downloads, and report management.
 - o **Nest JS:** This structure promotes better maintainability and scalability for larger projects such as this one.

Database:

- **MongoDB:** This is a **NoSQL** (Not Only Structured Query Language) document database that stores data in flexible JSON-like documents. This app uses MongoDB to store patient data, medical images, users' information, MongoDB's flexibility is useful for storing radiology reports and other application-specific information.
- **Cloudinary:** This is a cloud-based platform that specializes in managing digital assets, particularly images and videos, for web and mobile applications. The medical images are uploaded here and the obtained url (link) is stored with other patient information of MongoDB.

3.3.1.2 Other technologies

- **Redux:** A state management library for handling complex application state in React.js applications.
- **TailwindCSS:** It is a utility-first CSS (Cascading Style Sheets) framework that allows the rapid creation of modern websites without writing a lot of custom CSS codes.

3.3.1.3 Additional Considerations

Security: Since a teleradiology app deals with sensitive medical data, security is paramount. authentication, authorization, and encryption mechanisms to protect patient information. For this app the encryption is achieved using **bcrypt** and **salting** by password-hashing function. Additionally, access to the database is given to only selected IP addresses.

Scalability: Different modules can be added and integrated into existing functionalities with ease.

3.3.1 Prototyping

Several design iterations were created and evaluated during the prototyping phase of the webapp teleradiology system to ensure the best possible user experience and functionality. Stakeholders (radiographers, radiologists, hospital data managers, etc.) provided feedback to help enhance the interface and functionality, allowing for more seamless collaboration and image interpretation.

3.3.2 System Requirements

- **Hardware:** The system must be able to run on a variety of hardware platforms, including laptops, and desktops.
- **Connectivity and Browser:** The system must be able to connect to the internet and the system must be compatible with a variety of latest browsers including Google Chrome, Mozilla Firefox, Microsoft Edge, and Opera.
- **Security:** The system must be secure and protect patient data.
- **Usability:** The system must be easy (user friendly) to use by radiologists and other healthcare professionals.
- **Scalability:** The system must be scalable to meet the needs of a growing number of users.

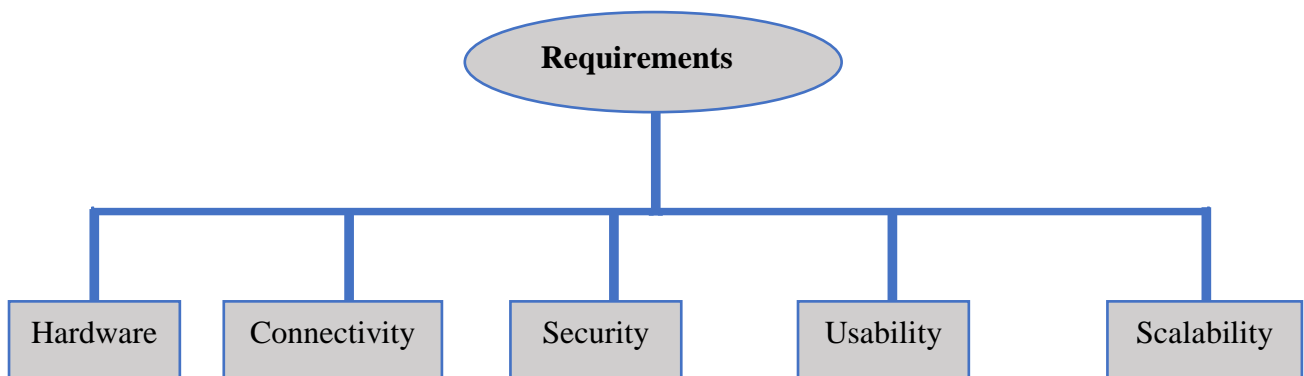


Figure 3-2: System requirements

3.3.3 System Components

- **Image Acquisition:** This component entails acquiring medical images using various imaging modalities such as CT scanners, MRI machines, and X-ray systems. These photos are collected digitally and prepped for transmission.
- **Image Storage and Management:** This component is responsible for storing and managing the acquired medical images. It incorporates a Picture Archiving and Communication System (PACS) that securely saves and organizes images for radiologists to easily retrieve and view.
- **Image Transmission:** This component focuses on the secure transfer of medical pictures from the source location (for example, hospitals) to the distant location (for example, radiologists' workstations).
- **The teleradiology workstation:** This is the interface via which radiologists' access and evaluate the sent medical pictures. The workstation often includes specialized software that offers picture viewing and analysis tools, as well as annotation, measuring, and reporting capabilities.
- **Remote Consultation and Collaboration:** This feature allows radiologists to virtually collaborate and consult with other healthcare providers. To ease communication and discussion of discoveries, such as real-time video conferencing, chat, and screen sharing

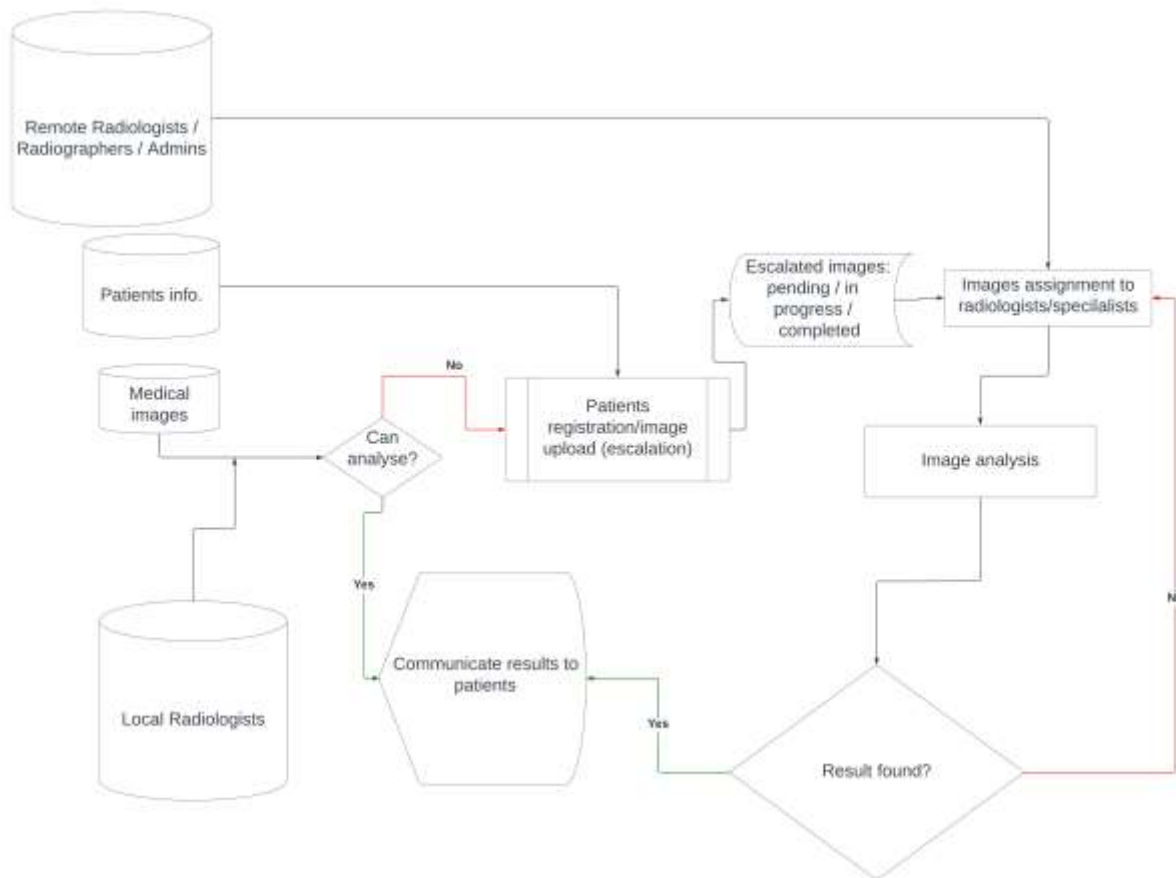


Figure 3-3: Teleradiology Block diagram

3.3.4 Development tools

Visual Studio Code is a lightweight but powerful source code editor which runs on your desktop and is available for Windows, macOS and Linux. It comes with built-in support for JavaScript, TypeScript and Node.js and has a rich ecosystem of extensions for other languages and runtimes (such as C++, C#, Java, Python, PHP, Go, .NET) [20].

3.3.5 Version Control with GIT and GitHub

Git is a free and open-source distributed version control system designed to Git is a distributed version control system that is free and open-source that can manage projects of any size quickly and effectively [21]. The version control system saves previous versions of a project and allows for easy restoration to that version. Furthermore, Git is used in team collaboration. Git offers a shared workspace for developers and tracks changes and modifications. This approach ensures that the project evolves as a whole from the outset, saving time by minimizing conflicts. In addition, GitHub offers code storage as it provides a safe and secure place to store codes. This is useful for backing up work done and sharing them with others.

Table 3-2: Major Cancer-Related Diagnostic Equipment in KFH

Type/Equipment	Summary
MRI (1 unit)	About half of all MRI scans are for cancer diagnosis. Reservations can be booked up to one month in advance. Approximately 8,900 cases (2021)
CT (1 unit)	Approximately 3,800 cases (2021)
General Radiography X-ray Systems (2 units)	In addition to general examinations, they are used for cancer diagnosis, and one unit is a digital type. Approximately 11,000 cases (2021)
Fluoroscopic Imaging System (1 unit)	Used for examination of the upper and lower gastrointestinal tract. Used for screening tests in combination with endoscopes. Approximately 6,400 cases (2021)
Mammography Unit (1 unit)	Used for breast cancer diagnosis. Biopsies are performed using an ultrasonic scanner. Approximately 880 cases (2021)
Ultrasound Scanner (1 unit)	Approximately 5,500 cases (2020) As of 2021, this reduced to approximately 800 cases because ultrasound examination is widely available in Rwanda.

Chapter 4: TESTING

4.1 Development testing

Software development testing, which takes place throughout the development phase, aims to detect defects early in the coding process. Developers or programmers are primarily responsible for writing unit tests to ensure that individual code blocks execute properly. This testing is done in the development environment, which is a separate location from where end users interact with the product.

4.1.1 User registration and Login to Web App Teleradiology

Registration

The users are registered by system admin, who is registered on the server side of the application. System admin will register the following information: **name**, **email** address (for login and communication), **password** (with password strength requirements) and **User role**: Specialist (radiologists), Referring physician (radiographer) and Admin.

Login

- **Page:** The user sees a form with fields to enter: Email address and Password.
- **Authentication:** The system verifies the email address and password against a secure database.
- **Login Success:** Upon successful login, users are directed to their personalized dashboard based on their user type.

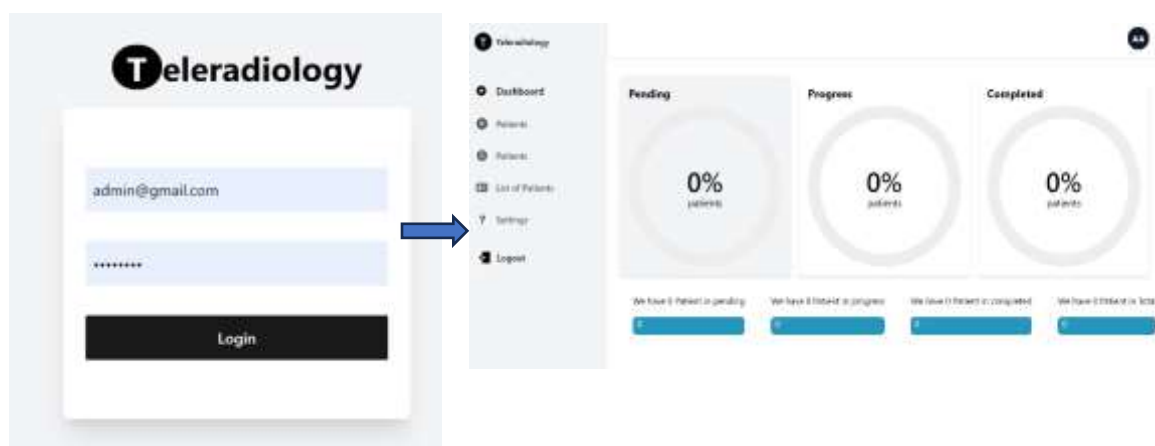


Figure 4-1: Login with the Registered user

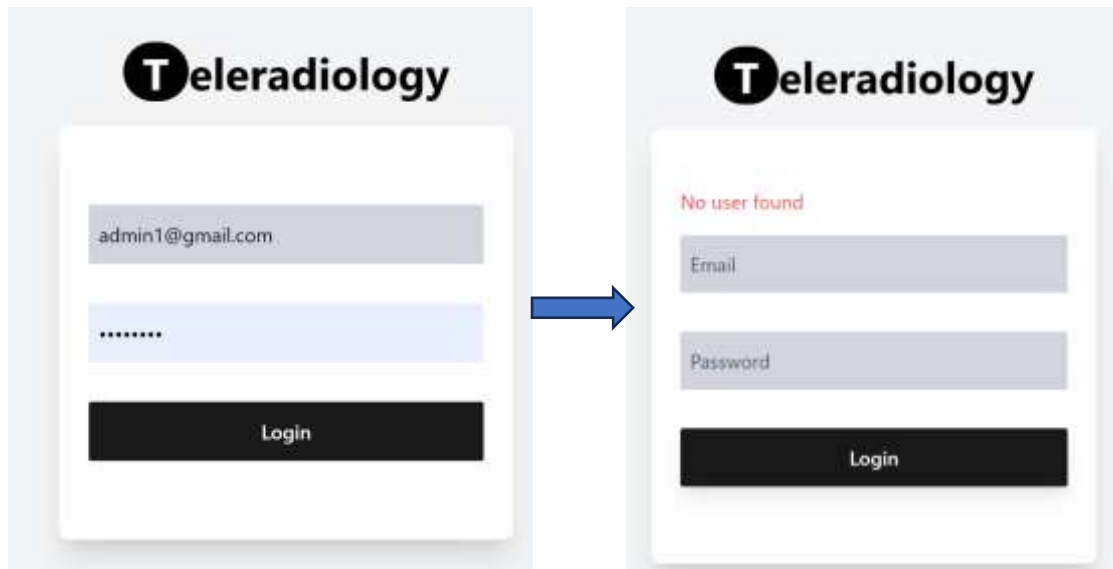


Figure 4-2: Login with unregistered user

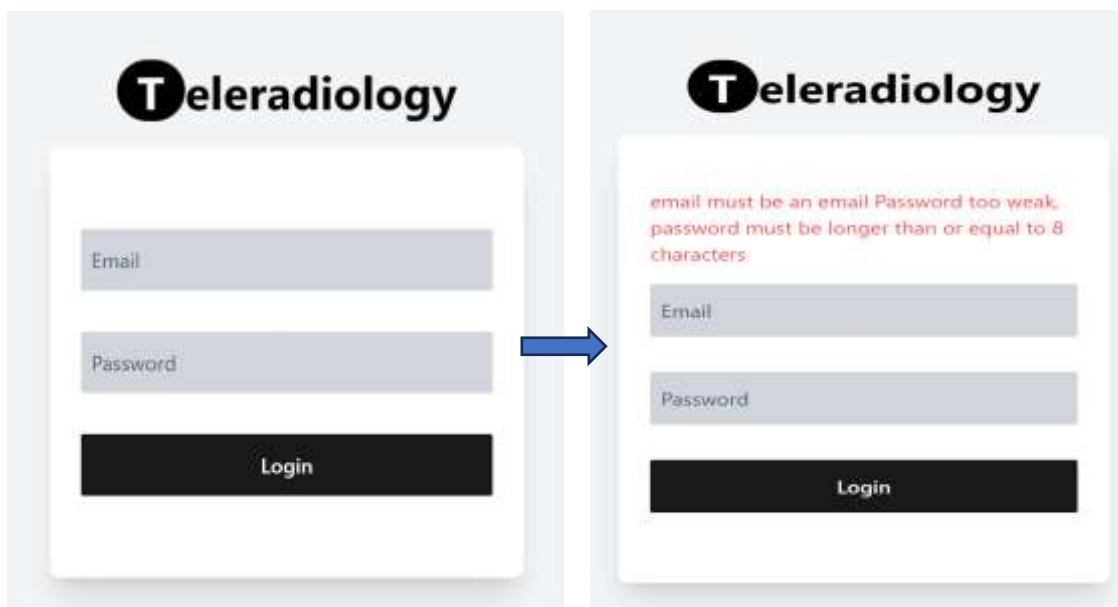


Figure 4-3: Login in with empty field

4.1.1.1 Radiographer successful login

The radiographers will land on the page where they will be able to upload images and add comments to the kind of help they are seeking from the radiologists.



Figure 4-4: User dashboard

The registration form includes a search bar, a table of patients, and a form to add a new patient. The table has columns for NAME, EMAIL, AGE, CREATED_AT, and ACTIONS. The form fields are for First name, Last name, Email, and Age.

NAME	EMAIL	AGE	CREATED_AT	ACTIONS
← Prev 1 Next →				

Form fields: First name, Last name, Email, Age. Add patient button.

Figure 4-5: Patients registration form

Choosing one patient for example, the radiographers will have the option to add a medical image required. Adding a clear description of the case so that the radiologists will know what is needed from the uploaded image and to interpret it accordingly.

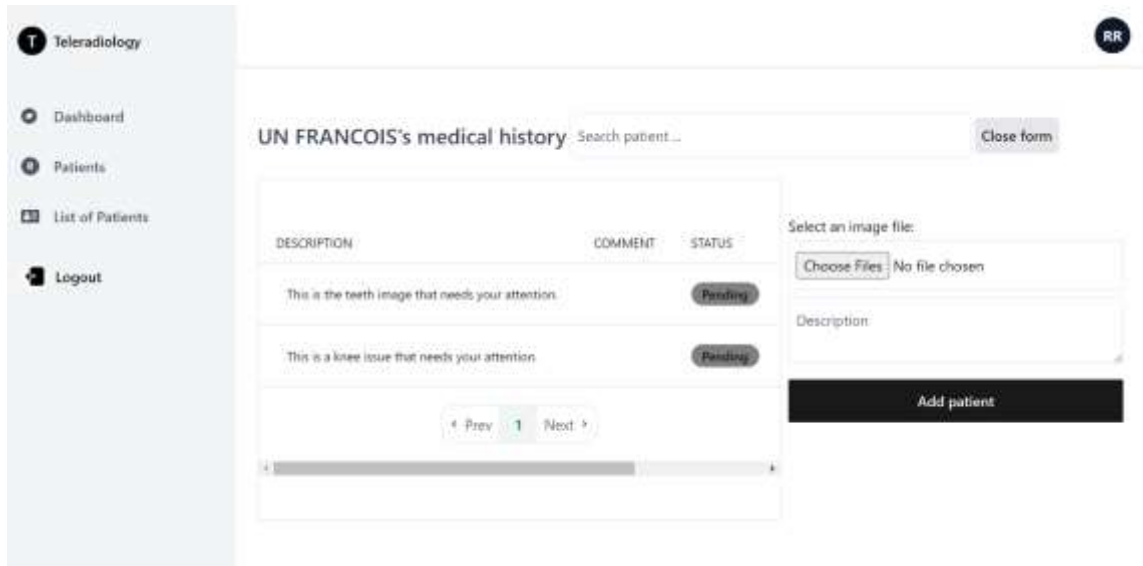


Figure 4-6: Medical History and image upload

4.1.1.2 Radiologists' successful login

The landing page is similar to that of radiographer, dashboard, as in Figure 4-4 above with the only difference being the top right corner, **RR** and **SS** for radiographers and specialists respectively.



Figure 4-7: Teeth image zoomed in to specific area of interest

The specialists also change the status of the cases uploaded from Pending to In Progress when images are being analyzed and completed when the interpretation is done and report generated. As can be seen in the Figure 4-8 and Figure 4-9 below.

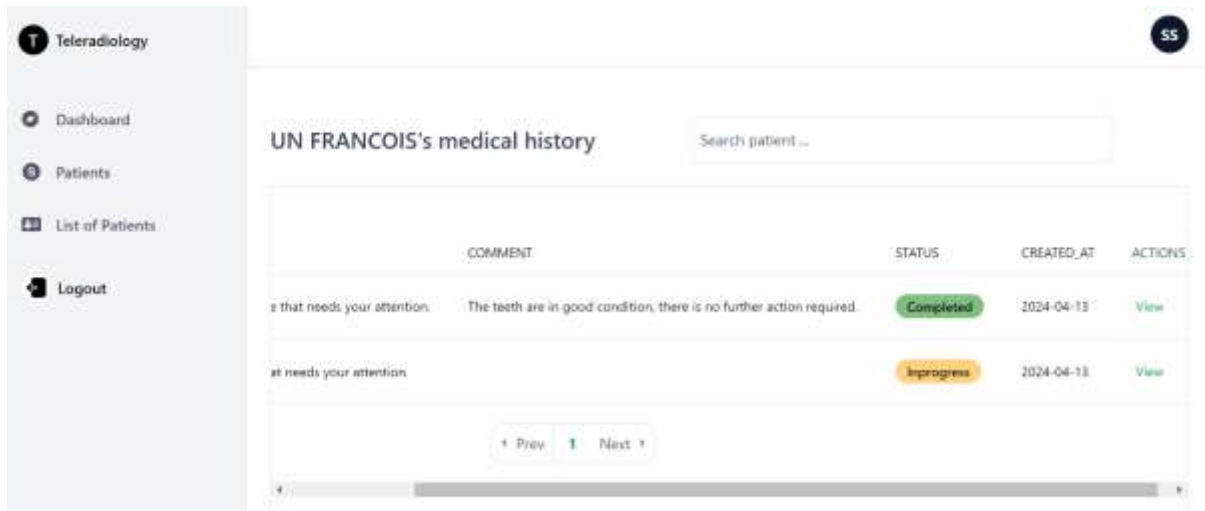


Figure 4-8: Completed and InProgress images status

If needed for the purpose of filing or any other reason, the users can print the printout of the report that includes the radiographer and specialist that have worked on the images and the comments made by them.



Figure 4-9: Medical report

4.1.1.3 Admin successful login

Upon successful login the dashboard will be quite different to that of the other two types of users in the system, with the addition of users management section as can be seen in Figure 4-10. The admins have the privileges to make certain users active and deactivate them based on the situation. Only the active users are the only ones that can login and use the application as in Figure 4-11.

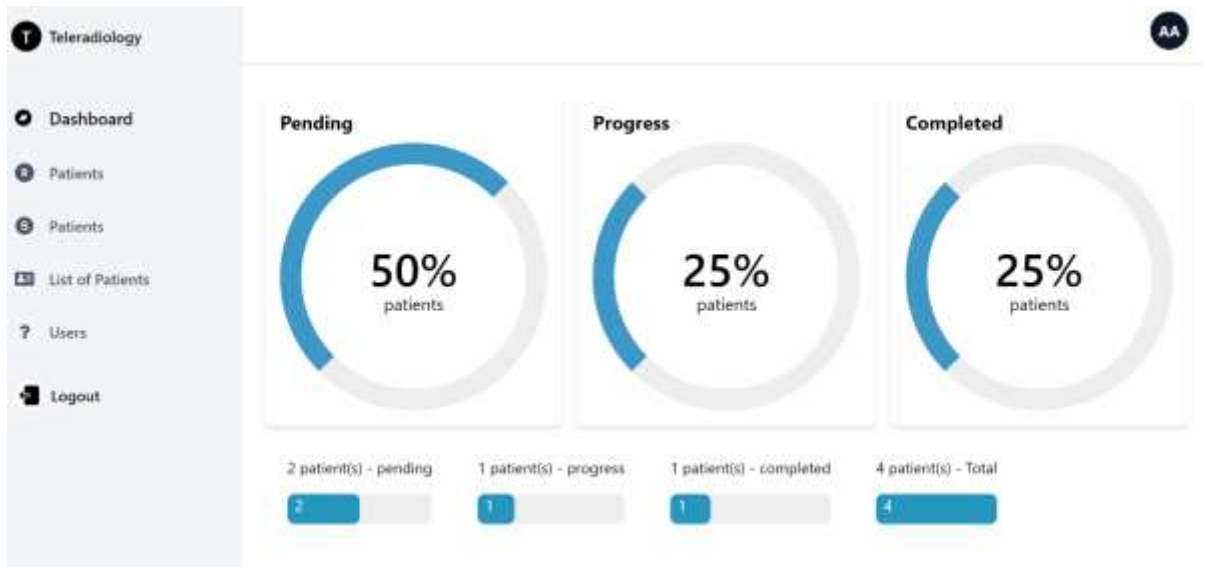


Figure 4-10: Admin dashboard

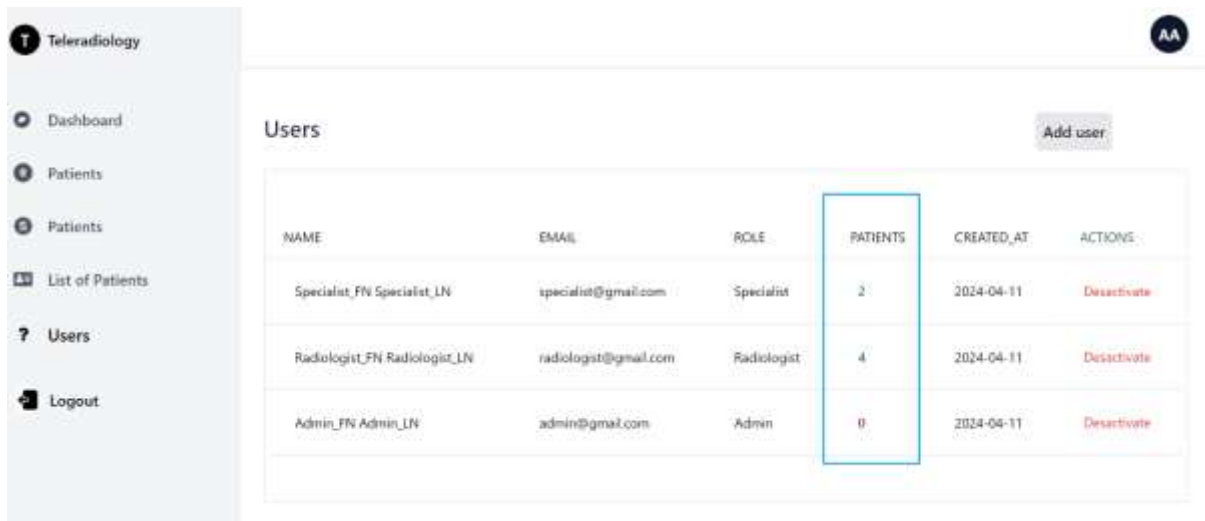


Figure 4-11: User management

The user section also indicates how many patients are assigned to a particular user, this will be for transparency and accountability as well as collaboration and workflow.

4.1.2 Adding users

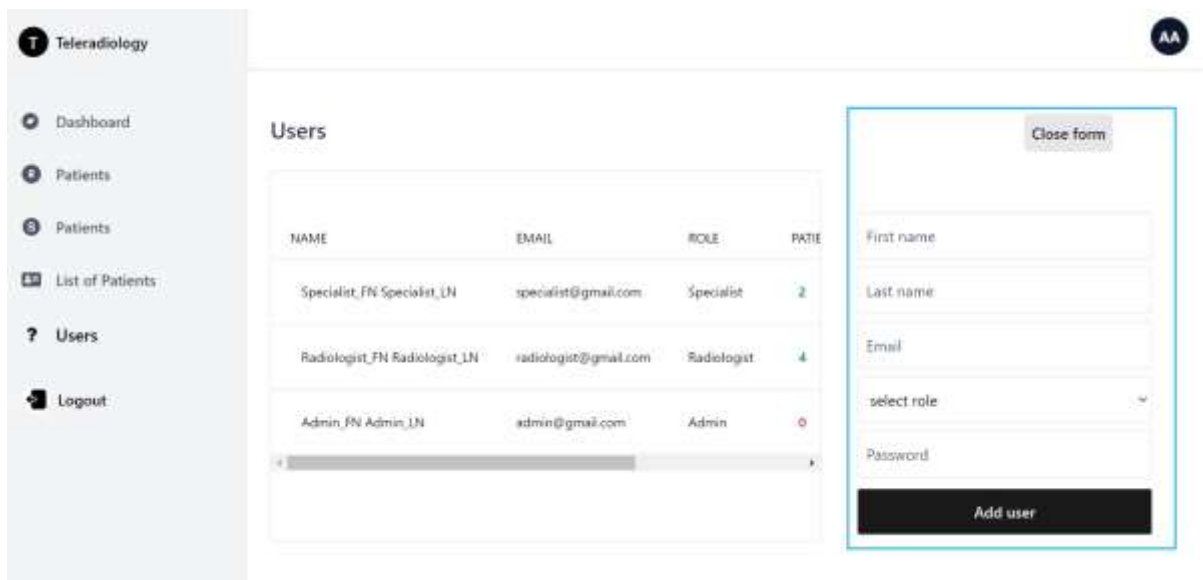


Figure 4-12: Adding users

The users are registered using their First name, Last name, Email, Role, Password. Email and Password are the ones that are used during application login.

4.1.3 Additional functionality

Other functionalities include but not limited to the following:

- Searching for a particular patient.
- Print patient list
- **Security:** App can only be accessible with authorized personnel and with specific IP addresses set for database access.

4.1.4 Future features and modules

This app developed here has the basic functionalities, and based on the needs of the application below are the future features and modules that will be integrated in the app.

- **Improved workflow management:** Create a system for monitoring the progress of studies and reports. This would enable radiologists to prioritize priority cases, track turnaround times, and maintain an efficient workflow.
- **Secure messaging:** Integrate secure messaging functionalities for radiologists to communicate with referring physicians regarding critical findings or complex cases.
- **Teleconferencing:** Enable teleconferencing tools so that radiologists can collaborate on complex cases with colleagues and carry out remote consultations with referring physicians.

- **Quality control:** Implement quality control modules to monitor radiologist performance and ensure consistent interpretations.
- **Mobile responsiveness:** The ability to adapt and display properly on various devices, including smartphones and tablets.
- **Integrate an Image Archiving and Retrieval System (PACS)** to store and manage medical images. This would create a centralized store for all patient photos that could be accessed by authorized people.
- **Advanced analytics:** Develop tools to analyze trends and generate reports on radiology metrics. This data can be used to identify areas for improvement in workflow, efficiency, and patient care.
- **Integration with other healthcare systems:** To facilitate seamless exchange of patient data and improve overall patient care coordination.
- **Machine learning integration:** Include machine learning methods to help radiologists with image analysis. This could include automating image segmentation, anomaly detection, and highlighting important regions of interest.

A functional prototype for a teleradiology web application has been successfully created. This prototype provides a comprehensive set of tools for remote interpretation of medical images. The deployed functions include secure user registration, login, activation, and deactivation processes for authorized access. Image acquisition enables medical images to be uploaded, stored, and transmitted efficiently and securely. Radiologists can remotely access uploaded images for interpretation using intuitive zoom features. Patient data confidentiality is protected throughout the workflow due to security measures. Users have the capability to generate and print imaging medical reports directly within the application. The source code can be found on the following github account <https://github.com/orgs/Web-App-Teleradiology/repositories>.

- **Image Zooming:** Users (radiographers and specialists) successfully zoomed in and out on images at different magnification levels, facilitating detailed analysis.
- **User Management:** The administration is allowed for the creation and management of user accounts.

5.2 Discussion

This prototype provides a solid platform for future growth and improvement. This demonstrates an effective and secure framework for remote image processing and collaborations. The successful implementation of features including picture upload, specialist remarks, user tracking and login attempts, IP-based access restriction, and image zooming capabilities meets the critical needs of teleradiology practice. The ability to add and manage users allows for effective administration and control over program access. These capabilities together lead to a more simplified and effective workflow, allowing for rapid diagnosis and treatment decisions in remote healthcare settings. Future improvements could include interaction with electronic health records, real-time image processing algorithms, and sophisticated collaboration capabilities to maximize the application's utility in teleradiology. This teleradiology web software prototype has the potential to boost efficiency, accessibility, and collaboration in remote radiology services and thus leading to improved healthcare provision. Through access to specialized expertise, improved diagnostic accuracy and efficiency, timely diagnosis and treatment, cost savings and resource optimization, and knowledge sharing and collaboration.

Chapter 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study presented the challenges posed by the limited availability of specialists skilled in interpreting medical images, such as CT-scans, MRI, and certain X-rays. The scarcity of specialists can lead to overworked radiologists, potentially causing delays in diagnosis and treatment, decreased quality of care, and increased costs to patients. In response to these challenges, a functional prototype for a teleradiology web application was developed. The prototype offers secure user registration, image upload, storage, and transmission capabilities, as well as remote image interpretation tools for radiologists. Provision of the ability to generate and print medical reports. The prototype serves as a strong foundation for further development, with potential future iterations. Overall, this teleradiology web application prototype has the potential to significantly improve efficiency, accessibility, and collaboration in remote radiology services, ultimately leading to improved healthcare delivery. The successful implementation of a teleradiology system in Rwandan hospitals can serve as a model for other healthcare systems confronted with comparable issues. Lessons from this research study can be shared with other countries or areas, potentially leading to the acceptance and deployment of similar teleradiology systems around the world.

6.2 Recommendations

6.2.1 To the research community:

- Conduct further research to evaluate the impact of this teleradiology system on patient outcomes, turnaround times, and radiologist workload.
- Explore the integration of artificial intelligence and machine learning for preliminary image analysis and decision support.
- Investigate the implementation of standardized protocols for image acquisition and reporting within the teleradiology system.

6.2.2 To the Government:

- Allocate funding and resources to support the implementation and scaling up of teleradiology initiatives.
- Consider financial incentives for hospitals to adopt teleradiology solutions and expand access to specialist interpretations, especially in district hospitals.

6.2.3 To the hospitals:

- Collaborate with teleradiology service providers to establish protocols for image acquisition, transmission, interpretation, and reporting that align with clinical best practices and regulatory standards.
- Train staff on the proper use of the teleradiology system and ensure efficient communication and collaboration.

6.2.3.1 To the end users:

- Participate in training programs and continuing education opportunities to develop proficiency in using teleradiology tools effectively.
- Actively engage in quality assurance measures, such as peer review and feedback mechanisms, to ensure the accuracy and reliability of diagnostic interpretations.

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APPENDICES

6.3 APPENDIX 1: Google form for Teleradiology

WEB APP TELERADIOLOGY FORM

I, UN Francois RUDASINGWA, am thrilled to introduce myself as a passionate and driven individual pursuing a Master's degree in Biomedical Engineering. With a strong foundation in engineering principles, I am eager to contribute my skills and knowledge to the advancement of healthcare technology.

I am conducting this research on **Design and Prototyping of the Web-based Teleradiology System: Case Study of Rwanda Hospitals** to gather information on the current situation on radiology system in Rwanda.

The information you provide will be invaluable in helping me to improve the current system and ensure that it meets the needs of patients, radiologists, referring physicians, and hospital staff.

Your participation is voluntary and all your responses will be kept confidential. The survey should take approximately 3-5 minutes to complete.

Please answer all questions honestly and to the best of your knowledge. Thank you again for your time and support. Attached below is my ethical clearance.

* Indicate required questions

1. Email *

- Radiographer Skip to question 4
- Radiologist Skip to question 10
- Referring Physicians Skip to question 77

Radiographer

4. How challenging do you find the current radiology workflow in Rwanda hospitals? * (e.g., referral intake, patient preparation, image acquisition, report generation)?

Mark only one oval.

- Not challenging at all
- Slightly challenging
- Moderately challenging
- Challenging
- Very challenging

5. How do you think a web-based teleradiology system could improve your work efficiency? *

Mark only one oval.

- To a great extent
- Somewhat
- A little
- Not at all

Ethical Clearance



COLLEGE OF MEDICINE AND HEALTH SERVICES
INSTITUTE FOR RESEARCH AND INNOVATION

ETHICAL CLEARANCE APPROVAL SHEET

Form: ETH/1/2022
Page: 01/01/2022

RU RUDASINGWA UN Francois (Mr. No. 20184242)
MSc. Degree Student in Biomedical Engineering
Centre of Excellence in Biomedical Engineering and Health (CEBHE), CHS, UR

Dear **RU RUDASINGWA UN Francois**:

RE: ETHICAL CLEARANCE

Subject: **Consent to your application for ethical clearance for the study entitled "Design and prototyping of the Web-based Teleradiology system: Case Study of Rwanda hospitals"**.

Having reviewed your application and been satisfied with your personal, cover study to handle patient ethical clearance. The ethical clearance is valid for you over starting from the date it is issued and shall be renewed as required. You will be required to submit the progress report and any other strategic results to the project during the implementation stage. In addition, at the end, the IRB shall need to be given the final report of your study.

We wish you good luck.

Assoc. Prof. Mutsa MUKURUMU
Acting Chairperson, Institutional Review Board,
College of Medicine and Health Services, Kigali, UR

CC:

Principal, College of Medicine and Health Services, UR
Secretary, Institute of Research and Innovation, UR

Email: research@ur.ac.rw | Tel: +250 786 8946 | Website: www.ur.ac.rw

Institutional Review Board

- Prepared
- Very prepared

7. How much training and support do you believe would be necessary for radiographers to effectively utilize a web-based teleradiology system? *

Mark only one oval.

- Minimal
- Some
- Moderate
- Extensive
- Comprehensive

8. How comfortable are you using web-based applications in your work? *

Mark only one oval.

- Not at all comfortable
- Somewhat comfortable
- Neutral
- Comfortable
- Very comfortable

9. How often do you encounter situations where referral information seems incomplete or unclear? *

Mark only one oval.

- Always
- Often
- Sometimes
- Rarely
- Never

Skip to question 22

Radiologists

10. How many radiologists (specialists) are in Rwanda? (Enter a number) *

11. How many imaging studies do you typically interpret on a daily basis? (Enter a range) *

12. Select your preferred method of communication with referring physicians for complex cases (choose all that apply) *

Tick all that apply:

- Phone call
- Secure messaging within the teleradiology system
- Video conferencing
- Written report addendum

16. How do you rate the image quality displayed on your workstation to be sufficient for accurate diagnosis? *

Mark only one oval.

- Not important
- Slightly important
- Moderately important
- Important
- Very important

Skip to question 22

Referring Physicians

17. How often do you seek help from specialists in diagnosis and image interpretation of patients? *

Mark only one oval.

- Always
- Often
- Sometimes
- Rarely
- Never

18. How often do you encounter situations where access to a radiologist delays patient diagnosis or treatment? *

Mark only one oval.

- Always
- Often
- Sometimes
- Rarely
- Never

13. How concerned are you about patient data security and privacy within a web-based system? *

Mark only one oval.

- Not at all
- Somewhat
- Moderately
- Vary
- Extremely

14. How do you anticipate the collaboration and communication between radiologists and referring physicians being affected by the adoption of a web-based teleradiology system? *

Mark only one oval.

- No change
- Minimal
- Moderate
- Significant
- Very significant

15. Please rate your anticipation of the impact of a teleradiology system on the quality and speed of diagnosis and reporting in Rwandan hospitals. *

Mark only one oval.

- Not at all helpful
- Unhelpful
- Neither helpful nor unhelpful
- Somewhat helpful
- Very helpful

19. How helpful would a teleradiology system be in improving communication and feedback regarding imaging results? *

Mark only one oval.

- Not at all helpful
- Not helpful
- Neither helpful nor unhelpful
- Somewhat helpful
- Very helpful

20. How comfortable are you using web-based applications? *

Mark only one oval.

- Very uncomfortable
- Somewhat uncomfortable
- Neutral
- Comfortable
- Very comfortable

21. Would you benefit from additional training on the technical aspects of web-based applications? *

Mark only one oval.

- Yes
- No
- Maybe

Skip to question 22

Importance of Teleradiology system

22. Rank the following features in order of importance for you in a teleradiology system. *

Mark only one oval per row.

	1	2	3	4	5
High-quality image viewing and manipulation tools	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Secure communication platform for interacting with radiologists	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Online training modules for system functionality	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Integration with existing hospital information systems	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mobile app access for remote image review	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

This content is neither created nor endorsed by Google.

Google Forms

6.4 APPENDIX 2: Google form for Imaging modalities

WEB APP TELERADIOLOGY

I, UN Francis RUSIMINGWA, am thrilled to introduce myself as a passionate and driven individual pursuing a Master's degree in Biomedical Engineering. With a strong foundation in engineering principles, I am eager to contribute my skills and knowledge to the advancement of healthcare technology.

I am conducting this research on **Design and Prototyping of the Web-based Teleradiology System, Case Study of Rwandan Hospitals** to gather information on the current situation on radiology systems in Rwanda.

The information you provide will be invaluable in helping me to improve the current system and ensure that it meets the needs of patients, radiologists, referring physicians, and hospital staff.

Your participation is voluntary and all your responses will be kept confidential. The survey should take approximately 3-5 minutes to complete.

Please answer all questions honestly and to the best of your knowledge. Thank you again for your time and support.

Attached below is my ethical clearance

* Red boxes required question

Ethical Clearance



COLLEGE OF MEDICINE AND HEALTH SCIENCES
INSTITUTE OF RESEARCH AND INNOVATION

ETHICAL APPROVAL BY THE BOARD

DATE: 27/11/2023
BY: CHAIRPERSON

UN Francis RUSIMINGWA (ID No. 2024020)
M.Sc. Degree Student in Biomedical Engineering
College of Medicine and Health Sciences and Institute of Research and Innovation

Dear UN Francis RUSIMINGWA:

RE: **ETHICAL CLEARANCE**

Reference is made to your application for ethical clearance for the study entitled "Design and prototyping of the Web-based Teleradiology system, Case Study of Rwandan Hospitals".

During the review process and after careful consideration, your study is hereby granted ethical clearance. The ethical clearance is valid from the date of this letter and shall be renewed as required. You will be required to submit the progress report and any other changes made to the project during the implementation stage. In addition, at the end, the IRB shall need to be given the final report of your study.

We wish you good luck in your study.

Yours faithfully,
Assoc. Prof. *[Signature]*
Assoc. Professor in Biomedical Engineering,
College of Medicine and Health Sciences, Institute of Research and Innovation,
UR

Principal, College of Medicine and Health Sciences, UR
Director, Institute of Research and Innovation, UR

Phone: 02522 20000 ext. 2000 | Fax: 02522 20000 | www.ur.ac.rw

1. 1. What is your name?

2. 2. Please specify your institution and position *

3. 3. How many Radiologists (specialists) in Rwanda by 2024?

4. 4. Please specify the number of Magnet Resonance Imaging (MRI) machines available in Rwanda.

Skip to question 2

4.1 MRI Machines location

5. Please specify the location of Magnet Resonance Imaging (MRI) machines in Rwanda

6. Please specify the number of Computed Tomography (CT) scanners available in Rwanda.

Skip to question 7

5.1 CT scanners location

7. Please specify the location of CT scan machines available in Rwanda.

8. Please specify the number of patients requesting for imaging services in Rwanda by 2023.

This content will be collected and stored by Google

Google Forms

6.5 APPENDIX 3: Ethical Clearance



UNIVERSITY of
RWANDA

COLLEGE OF MEDICINE AND HEALTH SCIENCES
DIRECTORATE OF RESEARCH & INNOVATION

CMHS INSTITUTIONAL REVIEW BOARD (IRB)

Kigali, 27th/12/2023
Ref: CMHS/IRB/563/2023

RUDASINGWA UN Francois (Ref. No. 215043302)
MSc. Degree Student in Biomedical Engineering
Centre of Excellence in Biomedical Engineering and E-Health (CEBE), CST, UR

Dear RUDASINGWA UN Francois

RE: ETHICAL CLEARANCE

Reference is made to your application for ethical clearance for the study entitled "*Design and prototyping of the Web-based Teleradiology system. Case Study of Rwandan hospitals*".

Having reviewed your application and been satisfied with your protocol, your study is hereby granted ethical clearance. The ethical clearance is valid for one year starting from the date it is issued and shall be renewed on request. You will be required to submit the progress report and any major changes made in the proposal during the implementation stage. In addition, at the end, the IRB shall need to be given the final report of your study.

We wish you success in this study.

Assoc. Prof. Stefan Jansen (PhD)
Acting Chairperson Institutional Review Board,
College of Medicine and Health Sciences, UR

Cc:

- Principal College of Medicine and Health Sciences, UR
- University Director of Research and Postgraduate studies, UR