UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE INFORMÁTICA
PROGRAMA DE PÓS-GRADUAÇÃO EM COMPUTAÇÃO

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Medical Image Analysis Based on Mobile and Virtual Reality Interfaces

Thesis presented in partial fulfillment
of the requirements for the degree of
Master of Computer Science

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Advisor

Porto Alegre, June 2017

CIP – CATALOGING-IN-PUBLICATION

Venson, José Eduardo

Medical Image Analysis Based on Mobile and Virtual Reality Interfaces / José Eduardo Venson. – Porto Alegre: PPGC da UFRGS, 2017.

75 f.: il.

Thesis (Master) – Universidade Federal do Rio Grande do Sul. Programa de Pós-Graduação em Computação, Porto Alegre, BR–RS, 2017. Advisor: Anderson Maciel.

1. Radiology. 2. Mobile Devices. 3. Healthcare. 4. Virtual Reality. I. Maciel, Anderson. II. Título.

“Once we accept our limits,
we go beyond them.”
— SIR ALBERT EINSTEIN

AGRADECIMENTOS

Primeiramente, agradeço meus pais Eliz Regina e José Valter que sempre me apoiaram em minhas decisões e não mediram esforços para que esse trabalho fosse concluído. Agradeço minha irmã Janaina e todos meus familiares que estiveram ao meu lado, inclusive nos momentos mais difíceis. Aos meus nobres amigos e a minha namorada Laura que mesmo distantes se fizeram tão presentes. As pessoas que acompanharam minha caminhada desde o início sabem o quão longe foi chegar até aqui.

Agradecimento especial ao meu orientador Anderson, que além de professor se tornou um amigo e aceitou o desafio de me orientar. Professor Anderson me ajudou a realizar sonhos, me ensinou a encarar grandes desafios e chegar a lugares até então inalcançáveis. Professor, registro aqui meu respeito e admiração.

Meu obrigado a todos os profissionais da Medvia Diagnóstico que participaram voluntariamente dos experimentos, principalmente para ao Dr. Fabio Onuki pelo incentivo e ensinamentos na área médica, atuando como um co-orientador e grande amigo, sem dúvidas terá sempre minha admiração. Também faço meu agradecimento a Animati - Computação Aplicada à Saúde, representada pelo Jean Carlo, por ser um exemplo de empresa que busca inovar em parceria com as instituições de ensino, e incentiva o crescimento dos seus colaboradores.

Agraciamento também as instituições, projetos e pessoas que financiaram o trabalho. Ao projeto "Appification of Medical Reports" financiado através do MCTI/SETEC/CNPq No. 17/2012 - RHAE. E também ao projeto do CNPq 305071/2012-2 e FAPERGS projeto 2283-2551/14-8.

Às pessoas especiais da minha vida, parte delas citadas aqui agradeço e dedico esse trabalho.

ABSTRACT

Radiology is considered the most digital medical specialty because of the diffusion of protocols and the digitization of processes. With fast technological advances, the imaging-based diagnosis remains in constant evolution and such changes have never had as much repercussion on the health workers as today. Our challenge as computer scientists is to propose new approaches that facilitate medical work, instigate collaboration and, finally, as the most audacious goal, improve people's healthcare.

In such context, this thesis investigates the use of alternative interfaces for medical images analysis. Our research is organized in two main areas. The first one concerns mobile diagnosis, from the development of tools that allow access to medical images in computation environments with limited resources, to the evaluation of the diagnosis performed in these environments when compared to traditional devices (radiological workstations). The second stage is related to advanced approaches to visualize volumetric exams. In this case, we investigate the diagnostic capability of visualizing in virtual reality, as well as the quality of the reconstructions provided in such environments, usability and user discomforts. All the experimentation and development were carried out on professional systems and validated by specialists in diagnostic imaging.

Techniques for efficient medical images access in environments with limited resources, such as tablets and smartphones, are the main contributions regarding mobile applications. This also includes a study of the typical behavior of radiologist physicians when using a mobile viewer and the respective usability evaluations of that application. For the mobile diagnosis, the high accuracy rate for the evaluation of computed tomography (CT), magnetic resonance imaging (MRI) and radiography when compared to desktop computers, stands out.

In addition, results obtained in the virtual reality visualization showed a highly accurate rate for the identification of superficial fractures (in 3D CT studies). The radiologists perception after using the immersive application has brought indications of what areas in medicine virtual reality can bring real benefits. Examples include surgeries planning, visualization of complex fractures and distraction of patients in painful procedures, among others.

In light of the presented results, the potential of the mobile devices for the evaluation of diagnostic images, mainly in cases of emergency, being fundamental for agility in the patients health care is noticeable. Virtual reality in radiology has the potential to revolutionize the interfaces for manipulation of clinical data, creating a new paradigm of interpretation in diagnostic medical images.

Keywords: Radiology, Mobile Devices, Healthcare, Virtual Reality.

Análise de Imagens Médicas Baseada em Interfaces Móveis e de Realidade Virtual

RESUMO

A radiologia é especialidade médica mais informatizada, graças a difusão de protocolos e a digitalização dos processos. Com os avanços da tecnologia, o diagnóstico por imagens se mantém em constante evolução e tais mudanças nunca tiveram tanta repercussão sobre o trabalho dor profissionais de saúde como agora. Nosso desafio enquanto pesquisadores de computação é propor abordagens que facilitem o trabalho médico, instigue a colaboração e, por fim, como objetivo mais audacioso, melhore os cuidados à saúde das pessoas.

Nesse contexto, esta dissertação investiga a inserção de interfaces alternativas para análise de imagens médicas diagnósticas. Ela está organizada em duas áreas principais, a primeira diz respeito ao diagnóstico móvel, desde o desenvolvimento de ferramentas que permitam o acesso a imagens digitais em ambientes com recursos limitados, até a avaliação do diagnóstico realizado nesses ambientes comparado a dispositivos tradicionais (workstations radiológicas). A segunda etapa está relacionada a visualização avançada de exames volumétricos, nesse caso investigamos a capacidade diagnóstica de visualizar em realidade virtual, bem como a qualidade das reconstruções nesse ambiente, usabilidade e desconfortos dos usuários. Toda a experimentação e desenvolvimento foi realizada sobre sistemas profissionais e validados por médicos especialistas em imagens diagnósticas.

As principais contribuições referentes a aplicações móveis são técnicas para acesso eficiente a imagens médicas em ambientes com recursos limitados, como tablets e smartphones, um estudo do comportamento típico de médicos radiologistas ao utilizarem um visualizador móvel e as respectivas avaliações de usabilidade dessa aplicação. Para o diagnóstico móvel, destaca-se a alta taxa de acerto para avaliação de exames de tomografia computadorizada (TC), ressonância magnética (RM) e radiografias, quando comparado a computadores desktop.

Além disso, resultados obtidos na visualização de imagens médicas em realidade virtual mostraram uma alta taxa de acerto na identificação de fraturas expostas (para imagens 3D de TC). A percepção dos radiologistas após utilizar a aplicação imersiva trouxe indicativos de quais áreas da medicina a realidade virtual pode trazer reais benefícios, como no planejamento de cirurgias, visualização de fraturas complexas, distração de pacientes em procedimentos dolorosos, entre outros.

À luz dos resultados apresentados, verifica-se o potencial dos dispositivos móveis para avaliação de imagens diagnósticas, principalmente em casos de emergência, sendo fundamental para agilidade no cuidado à saúde de pacientes. A realidade virtual na radiologia tem o potencial de revolucionar as interfaces para manipulação de dados clínicos, criando uma novo paradigma de interpretação em imagens médicas diagnósticas.

Palavras-chave: Radiologia, Dispositivos Móveis, Cuidados a Saúde, Realidade Virtual.

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LIST OF ABBREVIATIONS AND ACRONYMS

2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
ACR	American College of Radiology
CAVE	Cave Automatic Virtual Environment
CT	Computed Tomography
CV	Virtual Colonoscopy
DICOM	Digital Imaging and Communication in Medicine
GPU	Graphics Processing Unit
HMD	Head Mounted Display
LCD	Liquid Crystal Display
MIP	Maximum Intensive Pixel
MRI	Magnetic Resonance Imaging
MPR	Multiplanar Reconstruction
ODM	On-demand Download Manager
PACS	Picture and Archiving Communicated System
p	p-value from Statistical Analysis
SSQ	Simulator Sickness Questionnaire
SUS	System Usability Scale
VR	Virtual Reality

CONTENTS

1 INTRODUCTION

1.1 Motivation

Clinics and hospitals have been integrating their information systems in order to improve the quality of patient care services, following the concepts adopted worldwide. Current digital health technologies allow the creation of a large-scale network and image management systems, providing patient information and images to be shared and viewed locally and remotely.

However, in image-based diagnosis processes, radiologists interact with a dedicated workstation with especially designed and calibrated video monitors to interpret image exams. Besides high-end hardware requirements, these workstations must be equipped with often expensive picture archiving and communication system (PACS) and frequently depend on plug-ins installation. Such environments were developed for highly technical users trained in digital imaging, e.g. radiologists and medical physicists. This reality makes it difficult for other specialists, such as referring physicians (e.g. cardiologists, neurologists and surgeons) to access and understand the exams. Furthermore, as a consequence of the ever increasing use of teleradiology, several radiologists working outside the clinics and hospitals need to interpret the images remotely (GLAZER; RUIZ-WIBBELSMANN, 2011). In this context, a mobile viewer would allow immediate viewing by radiologists and other professionals without the need of being at a conventional workstation.

Mobile technology, in turn, has contributed to the management of chronic diseases, alerting people on medication schedule and improving the efficiency of health systems (WEST, 2012). Anywhere access through devices connected to the Internet is essential for patient care and particularly in emergency radiology. However, a medical application running outside the workstation environment has to deal with several constraints, such as reduced available memory and low network bandwidth. With the appropriate development approaches, mobile applications, wireless networks and software can be used with sufficient computing power, speed and complexity to allow for real-time interpretation of radiology studies (O'CONNELL; PATLAS, 2016; SZÉKELY; TALANOW; BÁGYI, 2013).

The inclusion of this new paradigm in medical image interpretation allows researchers to establish to which cases a mobile viewer can provide faster diagnosis, improved technical performance (accuracy of diagnosis) and ease of use compared with desktop image viewers (ZWART et al., 2015). For instance, instant mobile access by a a radiology subspecialty (e.g. neuroradiology) tends to provide more accurate diagnosis than workstation analysis by a general radiologist. In a previous study with patients with inconclusive diagnoses of appendicitis (SEONG et al., 2014), the smartphone based analysis by abdominal radiologists provided higher diagnostic confidence than the on-call workstation-based radiologists' preliminary reports.

A large variety of radiology-related smartphone applications are available with many potential benefits. However, the lack of knowledge about how the use of smartphones impacts image interpretation still hinders the widespread use of DICOM viewing applications in the clinical practice. Further research into the accuracy of primary diagnosis using such applications is needed (RODRIGUES et al., 2013). Another concern is the ergonomics of these applications for potential improvements in the development of radiology mobile apps (KIM et al., 2016).

Besides mobile diagnosis, more recently, Virtual Reality (VR) has also attracted interest of healthcare practitioners and providers. The most widespread application consists of 3D simulations for training or surgery planning. Virtual simulators have been especially successful in training minimally invasive and robotic procedures (BEURDEN; IJSSELSTEIJN; JUOLA, 2012).

In diagnosis, however, while 3D image acquisition is ubiquitous (e.g. CT and MRI), the outgoing images are still most often visualized slice by slice or printed out for posterior analysis. One reason is that 2D slices show both internal and external structures in one image. Spatial information, however, is lost. While volume visualization is capable of solving this problem, it faces the difficulty that more internally located structures may be occluded by structures near the surface (HÄNEL et al., 2014). In some specific cases only (e.g. planning surgeries and complex fractures), a visualization based on 3D volumetric rendering of the data is considered useful and is currently applied.

Even in such cases, the volume is exhibited as an interactive projection on conventional 2D screens and manipulated with mouse and keyboard. On the other hand, the recent popularity of 3D TV and theatres motivated the research on stereoscopic displays for spatial tasks in medical applications (ESCOBAR et al., 2015). Similarly, the widespread of off-the- shelf VR devices, e.g. Oculus Rift, has attracted the interest of healthcare professionals to a broader range of VR medical application.

The global medical imaging advanced visualization (3D/4D) software market generated U$1.8 billion in revenues in 2015 and is expected to reach U$3.2 billion in 2024, according to a new report by market research firm Transparency Market Research[1]. Market growth for this kind of software will be driven by several factors, including advances in computer technology, rapidly improving healthcare infrastructure worldwide, a growing number of patients and geriatric populations, and increasing demand for better imaging technology.

The advancement of this area requires a research effort to establish which cases really benefit from a VR interface. Besides, a thorough experimentation will be required to quantify gains for the medical workflow, the patients' health and the healthcare system as a whole.

Often, only the experienced radiologist fully understands the medical images. One key element of using VR in any application is that it renders a comprehensive and intuitive visual representation of the data even for the non-specialist. This opens the possibility to provide exam data to referring physicians that can be used for detailed surgery planning and communication with the patients during medical appointments. Another advantage of VR is that immersion in a virtual environment provides a theoretically unlimited field of view and volume space for the radiologist to organize both 2D and 3D (eventually 4D) data representations, maximizing the compromise between focus and context, increasing

[1] http://www.transparencymarketresearch.com/advanced-3d-4d-visualization-systems.html

the efficiency of the analysis (NI; BOWMAN; CHEN, 2006; TYNDIUK et al., 2004). This is crucial as the profusion of data to be analyzed by the radiologist grows fast as new acquisition modalities and diagnostic techniques evolve.

One of the possible innovations in the workflow is the generation of a 3D printed model of the patient specific-anatomy and pathology (RENGIER et al., 2010; SCHUBERT; LANGEVELD; DONOSO, 2013). This is especially useful with musculoskeletal images (FRIEDMAN et al., 2016). However, it is still expensive and limited in terms of modeling soft tissues and model modification. VR is a more flexible and inexpensive alternative.

1.1.1 Approach Overview

In this context, the research presented in this thesis explores the uses of mobile and VR interfaces for medical image diagnosis. Our studies are organized in three main experiments:

Firstly, related to mobile devices (Experiment I), we address two important problems that still prevent the global dissemination of mobile tools for diagnosis based on radiologic images. The first is the limited computational resources of mobile devices (e.g. network communication, computational power), and the second is the reportedly low friendliness of the user interface due to limited peripherals and underdeveloped specific design methodologies.

Then (Experiment II), we perform a multivariable user study to investigate the diagnostic concordance between image analysis based on mobile interfaces and conventional workstations. This is a major contribution, as the data we used and the experiment conditions are those from a real clinic (unfiltered). A singular aspect of our experiments is that they were applied on a distinct DICOM viewer that uses a combination of client- and server-side procedures to optimize the image transfer and visualization.

Finally (Experiment III), we report a user study to assess VR usage in the diagnostic procedure of fracture identification. Our premise is that VR technology allows for accurate diagnosis with high efficiency. Moreover, we report an exploratory study on the potential of immersive VR for other 3D image-based medical applications, such as virtual endoscopy, surgery planning and appointment with patients.

1.2 Research Questions

With our developed prototypes and these three experiments, we aimed at responding the following questions:

1. Is it possible to remotely access medical images quickly under unfavorable conditions and obtain performance equivalent to that of radiology workstations?

2. Is it possible to obtain an accurate imaging diagnosis using mobile devices?

   Which variables can impair the mobile diagnosis?

3. About virtual reality for medical imaging: how can immersive 3D aid in diagnosis and improve the medical workflow?

   Is it possible to identify bone fractures using a VR interface on 3D computed tomography (CT) scans?

1.3 Contributions

As consequence of our mobile and VR interfaces and experiments, the major contributions of this thesis are the following:

- A combination of client- and server-side procedures for efficient medical image access in diagnostic environments with limited resources (ex. mobile devices).
- Extraction of the typical behavioral pattern of radiologists when navigating through the image datasets.
- A confirmation of the high concordance between mobile and desktop devices for CT and MRI diagnostics, and the demonstration that it is possible to obtain a high concordance rate also for radiography analysis.
- With a new methodology that captures real cases in teleradiology, we obtained a higher diagnostic variance, which improves the generality of our conclusions.
- Investigating multiple variables that can impair the image interpretation with mobile interfaces, we found out that a high level of usability is perceived by the users.
- We found out that using compressed images and a small screen size does not affect image interpretation. We also found out which tools are necessary to perform diagnosis in each exam modality and/or body part.
- A user study to assess VR usage in the diagnostic procedure of fracture identification.
- A high level of effectiveness of the VR interface in identifying superficial fractures on head CTs.
- A radiologists perception of where VR applications can be useful in medicine.
- An engine able to apply multiplanar and volumetric reconstructions in tomographic imaging and run on wearable VR devices.

2 LITERATURE REVIEW

There are several initiatives to make the diagnostic procedures available beyond the workstation environment. In order to identify such initiatives, we conducted a review using the strings: "DICOM viewer", "Mobile radiology" and "Mobile diagnostic" in the Google Scholar search engine, and then selecting works with viewable results on desktop and/or mobile devices.

Previous studies have also explored the use of mobile devices, such as tablets and smartphones, in medical images analysis. A common feature of these studies is to verify the mobile diagnostic compared to conventional PACS workstations. Most often experiments occur with specific types of exams, e.g. computed tomography (CT) of abdomen, on the same DICOM viewer (generally the OsiriX mobile (CHOUDHRI; RADVANY, 2011)).

Regarding Virtual Reality, some initiatives investigate the viewing of medical images in immersive environments using caves or head mounted displays and alternative interaction forms. These studies comprise the understanding of anatomical structures and learning-training, surgery planning and diagnostic procedures (FOO; LOBE; WINER, 2009; LIN et al., 2013; BRIDGE et al., 2014; GALLO; PLACITELLI; CIAMPI, 2011).

This chapter presents the state of the art in diagnostics based on mobile and virtual reality interfaces. First, we present the techniques and approaches to make possible the medical imaging access on smartphones and tablets (Sec. 2.1). Then, we present many works that investigate the capability of the mobile diagnosis (Sec. 2.2). Finally, the initiatives related to immersive visualization and analysis of medical images are showed in the Sec. 2.3.

2.1 Mobile Applications

A more complete and widely used mobile application is the OsiriX mobile, whose implementation is described by Choudhri and Radvany (2011) . The application has tools for viewing and processing DICOM images, allowing users to perform several operations such as zoom and rotation, as show the Fig. 2.1. All images are downloaded to the application as uncompressed DICOM files, and then processed locally for all subsequent actions. This architecture affects the access time on networks with low bandwidth. As a result, the application does not allow the transfer of images larger than $1024x1024$. In addition, the application is only available for iOS, limiting the range of access devices.

Correa et al. (2008) presents an approach to extend the access of medical images on mobile devices. They developed a distributed system composed of a web server, responsible for processing computer aided diagnostics (CAD) algorithms on the images, and a mobile device client, which is able to visualize the results of such process. The

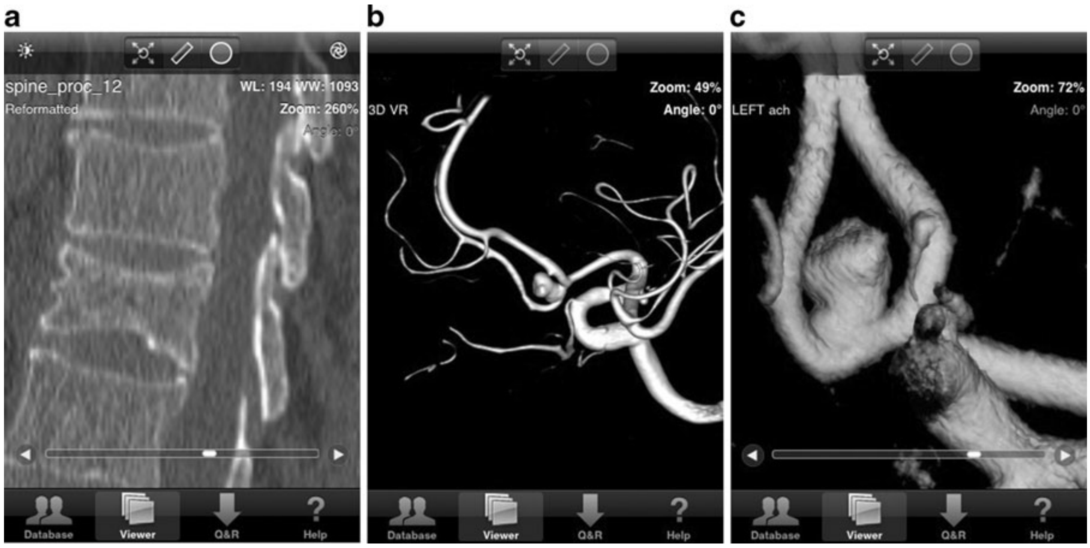


Figure 2.1 The OsiriX mobile application showing a sagittal CT of the thoracolumbar junction (a) and an MIP reformat (b) and three-dimensional volume rendering (c) (CHOUDHRI; RADVANY, 2011).

combination of both ends provide physicians with a solution containing extra information regarding the diagnosis. The system and user performance requirements for CAD, however, are not the same as for a visualization tool.

Similarly, Pasha et al. (2012) explore the use of mobile and stationary devices as a platform for collaborative discussion of medical images among hospital personnel. The patient images are uploaded from the workstation to a web server, which makes them available to mobile devices in the network. Using a mobile application that access the web server, the doctor can view DICOM images and collaboratively discuss the diagnosis with colleagues. The problem of limited memory available in mobile devices is mitigated by compressing large DICOM images to JPEG before sending them to the portable devices. Usability is not discussed.

Kaserer (2013) presents a DICOM web viewer able to display uncompressed DICOM files. Even though the viewer is able to run on desktop and on mobile platforms, it has some limitations, such as no integration with PACS systems and the limitation to display only uncompressed DICOM images. There is no performance evaluation.

2.2 Mobile Diagnosis

A more complete analysis regarding the use of the iPad for mobile on-call radiology diagnosis was presented by John et al. (2012). They analyzed 79 CT and 9 magnetic resonance imaging (MRI) studies common in emergency situation, interpreted by one radiologist on a full-featured desktop workstation and viewed independently by three radiologists on the mobile OsiriX. The comparison was made on two scales: major findings, minor findings. Results showed 3.4% (9 of 264) of major discrepancies and 5.6% (15 of 264) of minor discrepancies. These results suggest that the emergency conditions commonly encountered in CT and MRI can be diagnosed using a portable DICOM viewer with good concordance comparing to the workstation evaluation. However, the study is limited by the small number of participating radiologists (3). Another limitation is the comparison method, as they assume that the reports of the primary reporting radiologist were completely accurate. In our approach, the same radiologist prospectively reviews the studies on both platforms, avoiding this limitation.

Mc Laughlin et al. (2016) studied emergency **brain CT** in preliminary interpretation. They compared the image quality and diagnostic performance between an Apple iPad and a 2-megapixel monochrome LCD. Any reported discrepancies were recorded using the American College of Radiology (ACR) RADPEER system. They analyzed one hundred emergency brain CT exams. The tablet allowed satisfactory identification of acute brain CT findings, but additional research will be required to examine the cause of discrepancies that occur when using tablet devices.

Bhatia et al. (2013) demonstrated that mobile devices can display adequate resolution of CT and MRI sequences for diagnosing **acute central nervous system injuries** and other non-acute pathology. Five radiologists were included in this research and each independently interpreted specific exams on traditional high-resolution monitors (via eFilm software) as well as on an iPad mobile device (using OsiriX software).

For musculoskeletal exams, De Maio et al. (2014) analyzed the accuracy of mobile diagnostics related to **intra-articular knee pathology**. Fifty MRI studies of the knee followed by knee arthroscopy were prospectively evaluated. Two musculoskeletal radiologists independently reviewed each study using two different viewers: the OsiriX on an iPhone and eFilm conventional workstation. The authors concluded that an iPhone DICOM Viewer can be used and diagnosis results are similar to those obtained with a conventional radiology workstation. However, the mobile interface requires a significantly longer viewing time.

Park et al. (2013) examined the potential of the iPad 2 as a teleradiology tool for evaluating brain CT scans with **subtle hemorrhage**. They selected 100 brain CT exams performed for head trauma or headache. Five emergency physicians reviewed these studies using the mobile device and the LCD monitor, scoring the probability of intracranial hemorrhage on each exam on a five-point scale. The results showed high sensitivities and specificities between the two different analysis.

An early and reliable diagnosis at any time is crucial for an adequate treatment strategy for **abdominopelvic hemorrhage**. Given this assumption, Schlechtweg et al. (2016) researched one hundred patients with a clinical suspicion of abdominopelvic hemorrhage. CT exams were retrospectively read by two radiologists on a dedicated display and on a tablet computer. The results showed that this type of exam can be diagnosed on a tablet computer with a high diagnostic accuracy allowing mobile on-call diagnoses.

Kim et al. (2015) evaluated the feasibility of an iPhone-based system as a real-time remote CT reading tool for **suspected appendicitis** using a 3G network under suboptimal illumination. In total 120 abdominal CT scans were selected, 60 had no signs of appendicitis, whereas the remaining 60 had signs of appendicitis. Sixteen radiologists reviewed the images using the LCD monitor of a PACS workstation, as well as using a smartphone. They graded the probability of the presence of acute appendicitis using a five-point Likert scale. The overall sensitivity and specificity for the diagnosis of suspected appendicitis were not significantly different between displays. In another smaller abdominal CT study, Choudhri et al. (2012) obtained similar results using the same mobile viewer. Twenty-five abdominal studies were interpreted on an iPhone by five radiologists. **Acute appendicitis** was correctly identified on 98% of interpretations, **appendicoliths** were correctly identified on 88% of interpretations and cases of **abscesses** were correctly identified by all readers. Another related study of the abdomen, researched by Faggioni et al. (2015) showed that the mobile diagnostic was comparable in accuracy for detection of a**cute gastrointestinal bleeding** and can be significantly faster. A example of finding of this work is showed in the Fig. 2.2.

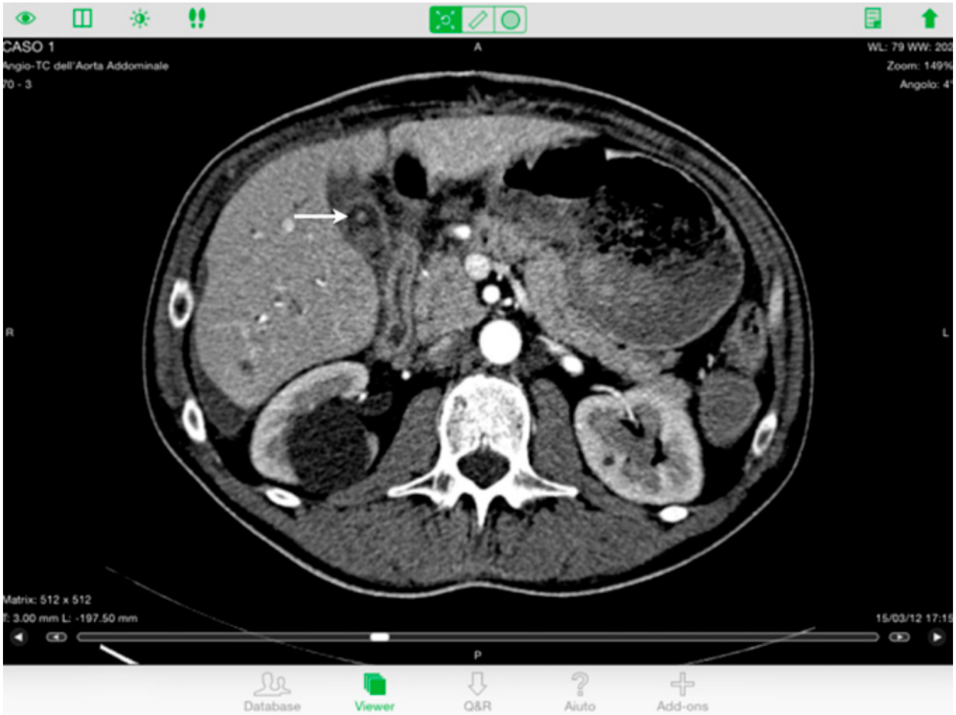


Figure 2.2 A case presented by Faggioni et al. (2015), where a axial CT image as displayed on the iPad showing a small contrast medium blush (arrow) in the arterial phase inside the duodenal lumen.

Park et al. [20] studied the performance of smartphone for reading coronary CT angiography in patients with **acute chest pain** at the emergency department (ED). 107 patients with acute chest pain who underwent CCTA and coronary angiography (CAG) were included. The degree of stenosis at each coronary segment was scored with a 4-point scale. The degree of stenosis at each coronary segments was also scored with preliminary report by on-call residents and final reports by cardiac radiologists. Interestingly, the smartphone-based reports were more concordant to the experienced radiologists' reports than those of on-call residents. Fig. 2.3 presents the mobile system interface during a 3D coronary CT viewing.

The potential of mobile devices has been shown even for images without diagnostic quality. Licurse et al. (2015) present the comparison of diagnostic accuracy of conventional radiography between the original film and smartphone capture (a photograph of the film). Forty-four radiographs were selected, consisting of 16 chest and 28 musculoskeletal radiographs. Both the smartphone-captured images and the original film radiographs were reviewed by two board-certified radiologists blinded to the diagnoses. The readers rated their confidence in the presence or absence of an abnormality in a five-point Likert scale. The majority of pathological features were detected on both conventional radiographs and smartphone capture.

Most previous works focused on evaluating specific categories of exams. We, instead, conducted an analysis with a wider range of examination procedures, including the digital

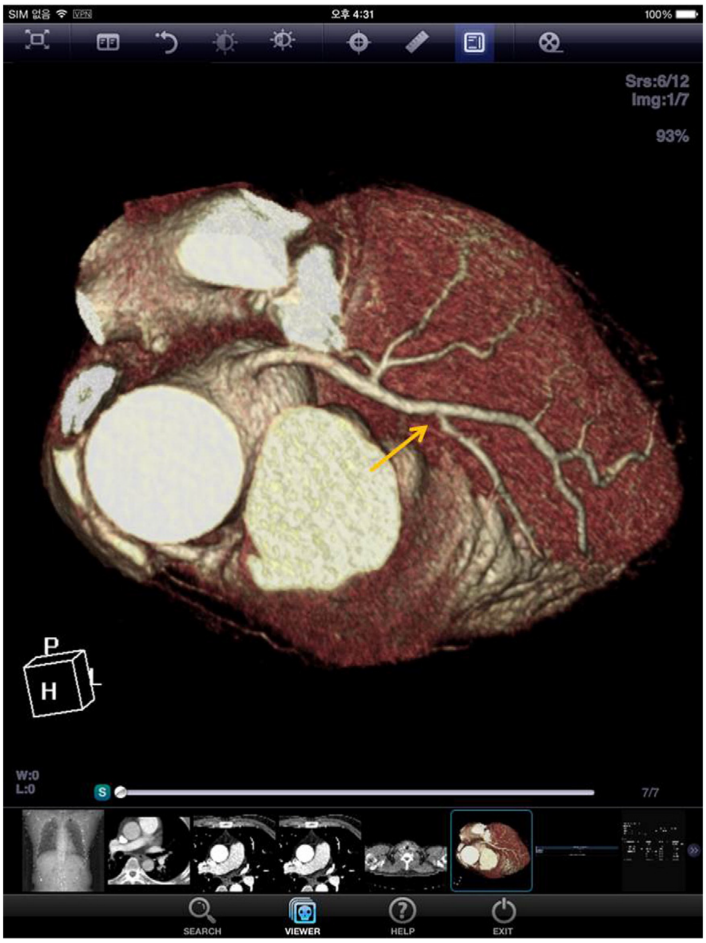


Figure 2.3 Display from a iPhone 5 using the mobile PACS application. The volume rendering image of the CCTA shows more than 50% stenosis at mid left anterior descending coronary artery (arrow) (PARK et al., 2016).

radiography modality. To the best or our knowledge, our work is the first to include evaluation information related to digital radiography. Furthermore, we investigated multiple variables that can impair the mobile interpretation, as well as the imaging tools and the application usability. Differently from previous studies, our experiment does not include pre-selected exams. Another novelty is the variety of radiologists from several specialties and levels.

2.3 Medical Imaging VR

A study by Ricciardi et al. (2015) presents a medical viewer for 3D environments usable on either a desktop, a head-mounted display or a CAVE. This system allows for inspection of CT and MRI sequences superimposed to the 3D volume made from those images. The software is able to simplify the understanding of complex datasets increasing the visualization realism of anatomical structures by enabling the user's depth perception of the models. No clinical application or evaluation is reported.

Similarly, Hänel et al. (2014) explore a combination of 2D and 3D images to provide a better understanding of structural changes in the brain of a person with corticobasal syndrome. This system allows the display on conventional monitors and immersive envi-

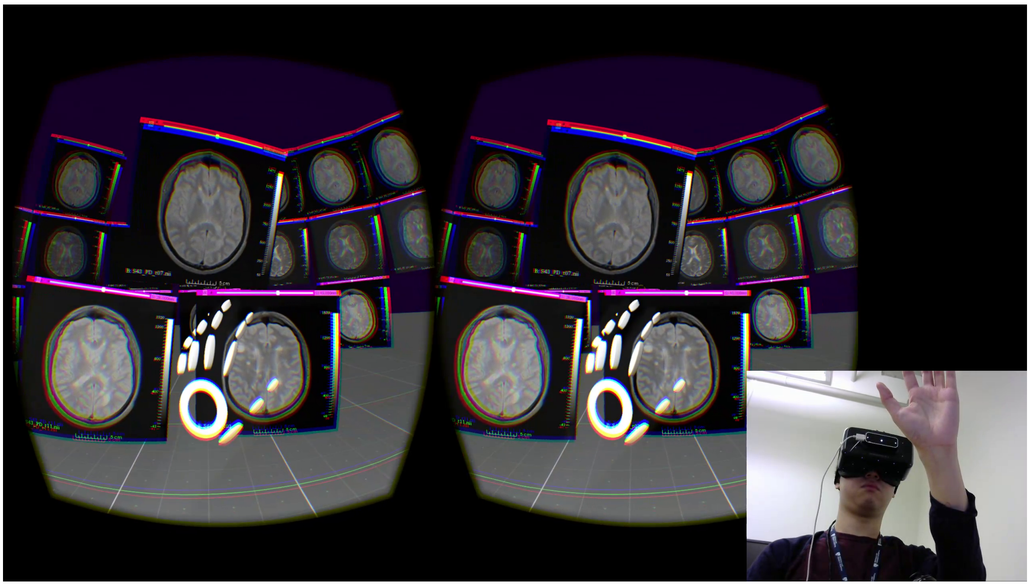


Figure 2.4 Hands-on positioning using the Leap Motion controller.

ronments with stereoscopic visualization to improve depth perception. The results show a significant improvement in the spatial localization of brain structures affected with this syndrome.

In diagnosis, King et al. (2016) presents an immersive virtual reality environment for the radiologist work. The study explores a larger screen area provided by VR in comparison with conventional monitors to optimize the volume of images analyzed simultaneously. An application with multiple 2D-only image views was developed on the Unity platform. It is possible to interact with the application through an HMD and to adjust images windowing with a leap motion or a game controller, as show the Fig. 2.4 where a user handles an amount of medical images with this interface. The system was used for CT visualization of a patient with a lung nodule and multiple-sclerosis lesion evolution of MRI dataset. Validation experiments for the usage of the system in differential diagnosis and remote collaboration were presented.

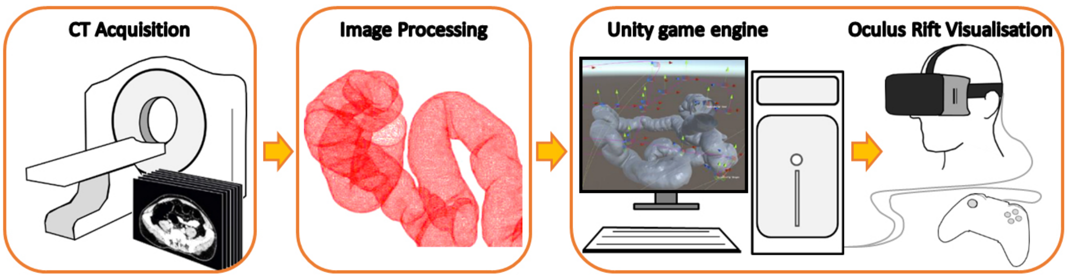


Figure 2.5 Schematic of the process used to produce an Oculus Rift for virtual colonoscopy visualization.

The Oculus Rift was explored in virtual colonoscopy (VC) procedure by Randall et al. (2015). Fig. 2.5 present the schematic of the process, where a preprocessed mesh is loaded into a virtual environment developed on Unity. Then, a VR camera is assigned to travel both outside and inside the colon, aided by joystick controls. Two radiologists and a gastroenterologist experienced the application, without clinical purposes. The results showed the potential of this technology to improve diagnosis, but emphasizes new future deployments to provide maximum performance. Likewise, Mirhosseini et al. (2014) studied the benefits of 3D immersion for virtual colonoscopy using a CAVE. The authors highlight the benefits of 3D interaction techniques to improve cancer screening in VC.

In these previous studies, the authors present their efforts to establish new techniques of 3D immersive visualization and interaction in medical context. Nevertheless, the VR technology is not widely used in routine medical procedures, such as diagnostic image analysis. Our approach evaluates the diagnostic effectiveness and quality of 3D volumetric reconstructions made for current VR devices.

3 APPROACH OVERVIEW

3.1 Methodology

As presented in the introduction, this thesis is organized in three main parts based on medical radiologists user studies that build upon each other as follows.

Both experiments I and II, correspond to research related to the project "Appification of Medical Reports" funded by CNPq and executed by company Animati with partner institutions. This project aims to keep the product Animati Viewer in constant technological evolution.

Experiment I, Mobile application. We validate the computational approaches that aim to optimize access to medical imaging using mobile devices, presented by the authors in Venson et al. (2015). The results of this experiment are presented in the Chapter 4 of this dissertation and also in Venson et al. (2017) .

Experiment II, Mobile application for medical diagnosis. We designed a new experiment motivated by the good evaluation of the speed of access and the image quality obtained in the previous experiment. In this experiment, the objective is to measure the diagnostic capability of our application compared to the conventional interpretation made on desktop devices. Along the Experiment II, we conducted a field survey about the medical interest in the insertion of new technologies in their work flow, as well as about the importance of 3D images in diagnostic procedures. This research was carried out due to a second project related to this thesis, called "Advanced visualization of diagnostic images on mobile and wearable devices". The project was executed by the same company and partly funded by the program Tecnova-RS[1].

Experiment III, Medical imaging VR. With the interesting results of field research applied in the experiment II, we conducted a third experiment regarding advanced 3D image visualization using virtual reality technology. The experimental setup and results are described in the Chapter 6, in Venson et al. (2016) and Venson et al. (2017).

The experiments were carried out with the database and volunteer professionals of Medvia Diagnóstico[2], a teleradiology located in Porto Alegre-RS, which receives approximately $28k$ image exams per month, from the five Brazil's macro-regions.

We have implemented our approaches on a real PACS system, the Animati PACS, a commercial software for distribution and image diagnostics developed by Animati - Computing for Healthcare[3]. We focused on improving the mobile application called **Animati Viewer**, part of this solution. The company and the Animati PACS are ANVISA (National Health Surveillance Agency) approved, which reflects our commitment to follow

[1]Tecnova Program - http://www.tecnova.rs.gov.br/
[2]Teleradiology Medvia - http://medvia.com.br
[3]Animati - http://www.animati.com.br

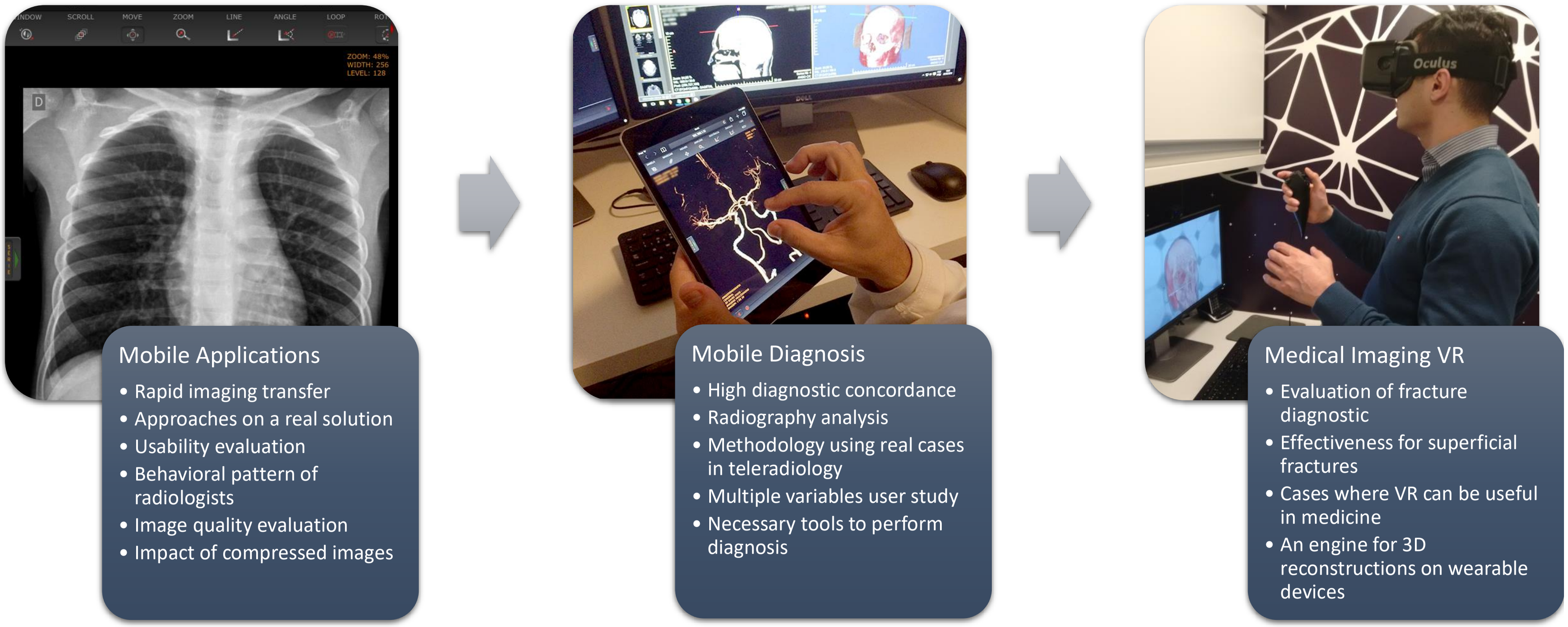


Figure 3.1 Context overview. First, the mobile application performance, behavior and results. Next, the diagnostic concordance study between mobile and conventional reading workstation. And then, the VR medical imaging research.

the regulatory and national standardization policies.

Animati is regarded as one of the leading systems for radiology workflow solutions in Brazil, having plenty of successful cases that are spread all over the country, reinforcing the commitment of our studies.

Fig. 3.1 present the context overview of the three experiments, and groups the main contributions from each of them. The architecture as well as the results of the respective experiments are described in the following chapters: Mobile Applications, Mobile Diagnosis and Medical Imaging VR. All the supplementary material to this thesis is available at www.josevenson.com and in the Appendix Section.

3.2 Ethics issues

Informed consent was obtained from all individual participants included in the study (See Appendix B). All procedures performed in our studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1975 Helsinki Declaration and its later amendments or comparable ethical standards. It has been approved by UFRGS (report number: 1.782.728). This work does not contain any studies with animals performed by any of the authors.

The experiments were not used in patient care and were not part of any diagnostic procedure. Participants were invited from among the physicians associated with the institution where our research was conducted. Invitations were made by personal contact whenever possible, and when not possible the invitation was sent via email. Afterwards, we set a schedule with interested users, guaranteeing the free participation or non participation of the subjects in the project.

4 EXPERIMENT I - MOBILE APPLICATION

In this experiment, we present the approaches for efficient medical imaging access in environments with limited resources. The main contribution of this study is the introduction of an approach that uses a combination of client- and server-side procedures to dynamically optimize the data flow for fast image transfer and visualization on mobile devices. The main advantage of our approach is to minimize the amount of data transferred to and used in the host device without sacrificing the user experience.

The remainder of this chapter defines requirements for diagnosis tools, describes our design assumptions and algorithms, characterizes the experimental setups and extensively discusses the results. Interesting findings regarding the typical behavioral pattern of radiologists when navigating through the image datasets are, for the first time, also presented in this thesis.

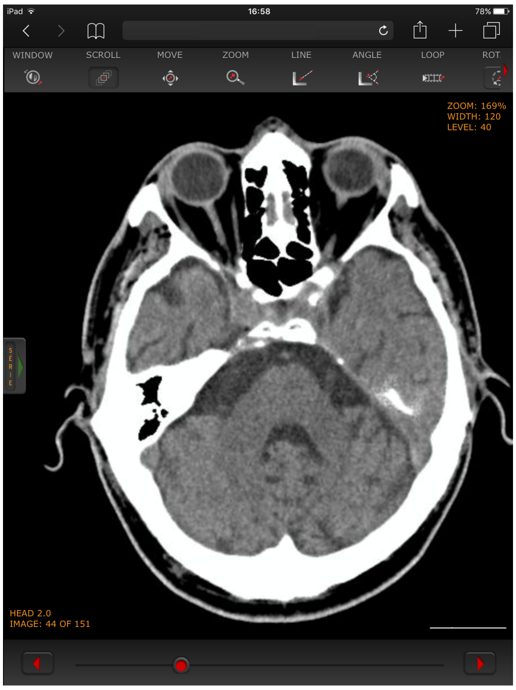
The results of these experiment were also presented in Venson et al. (2015) and Venson et al. (2017) . This chapter is organized in the following sections: system design and implementation, experimental setup, results and discussion.

4.1 System design and implementation

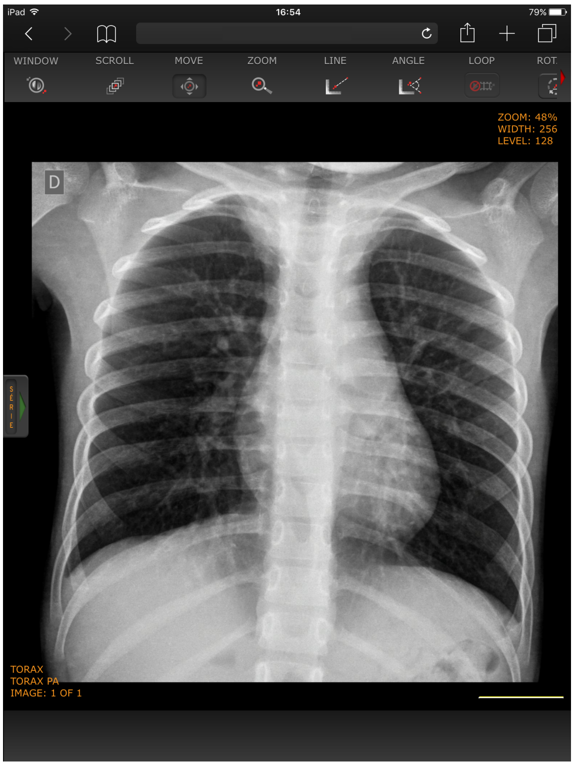
Our approach to creating a mobile DICOM viewer aims to reduce to a minimum the amount of information downloaded and processed by the application. This goal is achieved by orchestrating the on-demand download manager module (ODM) The approach use compression and cache strategies, as well as a combination of client- and server-side processing to reduce the amount of transferred data.

The ODM is the means to efficiently visualize the images in the series. It is controlled by the image selector, a slider widget represented by the red circle at the bottom of Fig. 4.1a and 4.1b. As the user slides the image selector over the sliding area, a specific image of the series is selected. Assuming the image selector is at position P and the series has 100 images, for instance, P can vary from 0 (far left side of the sliding area), which displays the first image of the series, to 99 (far right side), which displays the last image of the series. This approach allows the user to navigate back and forth through the images of a series. The currently active position/image P is called the pivot and it is used by the ODM to control the flow to fetch data from the server, deciding how many and which images should be downloaded.

(a) Head MRI.



(b) Head CT.



(c) Thorax radiography.

Figure 4.1 Examples of the application interface for 3 exams: Head MRI (a), Head CT (b) and conventional radiography (c).

4.1.1 On-demand Download Manager

The on-demand download manager (ODM) acts as a new level in the memory hierarchy. When the user opens a series, ODM fetches the corresponding images of that series from the server. In order to save on data transferring and comply with any memory constraints, the ODM module will fetch only a subset of the images from the server, storing them in a local buffer.

As soon as the first image is downloaded by the ODM, the user can navigate the series by sliding the image selector (pivot), as previously explained. The subset of images downloaded into the ODM buffer will always be centered at the position of the pivot. For instance, assuming the device is able to store 5 images in the ODM buffer and the pivot P is at position 5 ($P = 5$), the buffer will contain the images $\{3, 4, 5, 6, 7\}$, in that order. For every change in the position of the pivot, the ODM will calculate and decide new fetches. Using the previous example, if the pivot suddenly moves to position 7 ($P = 7$), the ODM will re-centralize the buffer around the pivot, fetching more images from the server (i.e., images 8 and 9), placing them to the right of the pivot; the ODM will also discard the images to the left (i.e., 3 and 4) to make room for the upcoming images being downloaded.

The resulting buffer will contain the images $\{5, 6, 7, 8, 9\}$. The ODM will always try to make the pivot the central image in the buffer, which means it will fetch images to the left and to the right of the pivot until the buffer is full. As a consequence, the user will be able to navigate back and forth with the image selector while the ODM controls the download process in the background.

The centralization approach of the ODM was designed based on a set of empirical viewing cases provided by medical specialists, presented by Venson et al. (2015) . The size of the ODM buffer defines how many images are stored in the device at any given time. Such size depends on the memory constraints of the hosting device. According to Wang et al. (2011) the size of a web-browser cache is about 300MB for desktops. This is several times larger than the 6MB available in the Android Gingerbread browser cache, for instance. For that reason, the ODM automatically adjusts its buffer size to meet the memory constraints of the host system.

As an additional optimization, all images downloaded by the ODM are JPEG files compressed with quality 75, which minimizes the amount of memory space required by the ODM to operate. The impact of this decision was measured through the user's perception of the images quality. This optimization was used to ensure that the viewer application would meet the memory constraints of the system it is running on. A CT exam, for instance, typically contains 500 images in a study, which accounts for 250MB of data (PIANYKH, 2008). Without the ODM and its subset/centralization strategy, the viewer would have to download all images of the study, which could be impractical on mobile devices, or download each image on demand, which will cause unbearable waiting times. The imposed size limit of the ODM buffer, however, allows an estimation of the amount of memory that will be consumed by the application. It can be calculated by averaging the size of each image in a study and multiplying that value by the size of the ODM subset.

In an empirical test, we measured the memory space required to analyze a CT study containing 3760 slices/images (JPEG compressed). If all images were downloaded and stored in memory, a maximum amount of 134.5MB would be used in the host device. Using the ODM and its strategy of downloading a subset of images at any given time, a maximum amount of 7.5MB of memory was used instead. The amount, in this case, is about 5% of the total size of the study, which can be estimated and adjusted according to the available resources.

4.1.2 Experimental setup

We designed and carried out experiments with real users to evaluate the performance of the proposed techniques. The main goal was to measure the effectiveness of our solution as a support tool for medical workflow. Part of this research was conducted at the premises of a partner teleradiology company. The company receives exams from dozens of clinics located in different towns spread on a radius over 500 km, causing large variance in the equipment and protocols used for image acquisition. This indicates that any results we shall obtain derive from real world data, which accounts for their validity in a general scenario.

Seven radiologists participated as volunteer users in the experiment (57.1% aged 31 to 35 years, 28% aged 36 to 40 and 14.3% aged 41 to 50). Six of them declared to be experienced radiologists. They have several subspecialties, e.g. neuroradiology, musculoskeletal, abdominal and thoracic. They are active professionals with appointments also in other clinics besides our partner's and hospitals, having large experience with PACS.

For our experiment, these doctors performed a total of 40 image analysis events without clinical purposes. Firstly, all participants signed a legal term of consent informing about the compliance with ethical precepts. Afterwards, they filled a characterization form. Then, they were invited to perform a diagnosis task using our software application installed on a tablet device. After the task conclusion, they should fill a user experience questionnaire.

During the experimental task, we captured the application log to evaluate ODM performance, as well as the user behavior while they perform the exams analysis. The user's perception about the quality of the images was also evaluated, by using a Likert scale ranging from 1 (poor for diagnosis) to 5 (very good for diagnosis).

Data from CT, MRI and radiography were used, as they represent, together, all expected visualization behaviors. Table 4.1 summarizes the selected modalities and specialties. This selection also considered the frequency of occurrence of these cases in emergency. This is important because a mobile viewer is particularly useful in emergency, as it allows for rapid access to images through the network, which means early assessment and treatment for the patient.

Table 4.1 Image modality distribution along body parts for the 40 events studied. Notice that we focused on cases that are especially common in emergency.

Body region	Radiography	CT	MRI
Head an neck	2	10	5
Abdomen and thorax	5	6	–
Bones and articulations	8	2	2

The studied events have been selected from the partner clinic's database, anonymized and distributed according to the participant's specialty. They were stored in a PACS server located 300km away from the user, which accurately simulates the average real case of mobile access in which the device is connected to an external network to the clinic. During the image analysis by the radiologists, the system captured a log of all operations performed on the interface, such as zoom, windowing and slice navigation. The tablet used in the experiment was an Apple iPad 3 mini with 1 GB of RAM and connected to a wifi network 10Mbps shared by multiple users.

4.2 Results

The following subsections present the results obtained with our experiment. These results are categorized and discussed according to their connection to the observed user behavior while interacting and the on-demand download manager.

4.2.1 Behavioral pattern for user interaction

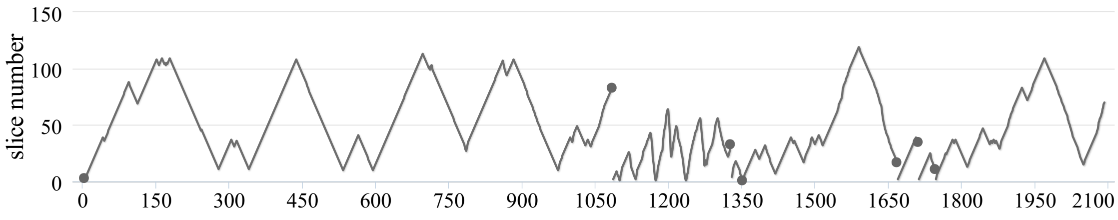
We observed two main usage patterns among the users during the analysis of the exams. The first one is that windowing actions are not needed for all situations. The second one is that the navigation among images of a series (performed by sliding left/right the image selector) is continuous and linear. As a consequence, if the current image being displayed is image 5, for instance, the next one more likely to be viewed is image 4 (previous) or 6 (next).

Regarding windowing actions, in 17 out of 40 tests (42.5%) the radiologist performed a windowing action, while in 23 tests (57.5%) no windowing action was performed at all. When this information is grouped by exam type, in the 18 CT exams performed, 9 of them (50%) featured a windowing action; in the 7 MRI exams, 4 of them (57%) presented a windowing action, 3 (43%) did not present any; in the 15 radiographies exams, 4 of them (26%) featured windowing actions, 11 (74%) had no windowing actions.

In summary, less than half of the exam analyses required windowing, and when radiography is used, only about 25% of the exams underwent windowing. The main reason for a windowing action not be required in the majority of exams is that the image acquisition protocol is often set to the average ideal window for each specific tissue and/or disease. Besides, depending on the exam, more than one protocol is used in such a way that an image is already available in different versions with varied windowing parameters. This is usually enough for the radiologist to make the analysis regardless of any extra windowing action.

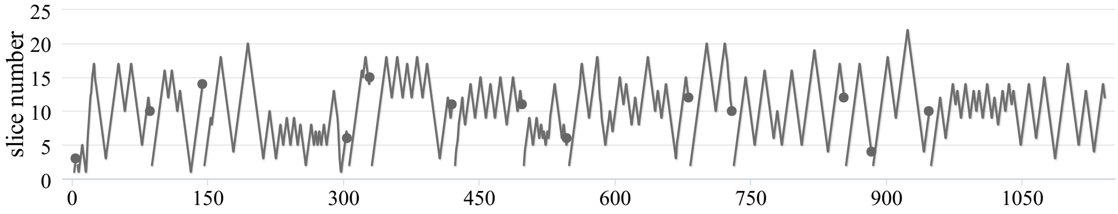
Regarding the behavior when visualizing a set of images/slices, Fig. 4.2 illustrates the navigation pattern using the image selector during the analysis of four different exams. The y-axis represents the image that is currently being displayed (pivot), while the x-axis represents the event of exhibition of one image regardless of the time spent with each image (this equalization of the Δt was necessary for better visualization of the chart). An ascending line in Fig. 4.2 means the image selector is being slided to the right; a descending line means a slide to the left. The circles indicate when the user changes to a new series of the exam. We selected the four cases presented in Fig. 4.2 as each of them represent a distinct group of exams.

The design of our ODM was based on empirical information that the user visualizes an image/slice more than once. The observed results confirm such behavior with statistical significance for exams with several images, such as CT and MRI, as illustrated in Fig. 4.2. The linear navigation pattern is explicit, as the user navigates throughout a series moving back and forth (sliding the image selector left and right), especially in specific areas of interest for the diagnosis process. Such navigation pattern is not connected to the number of images/slices in a series.



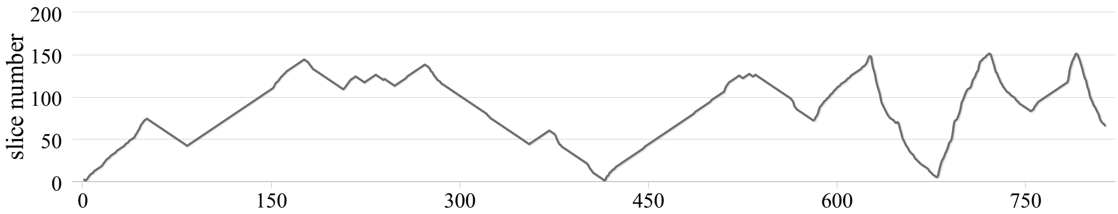
(a)

(a) CT of the head with 9-324 (series-images).



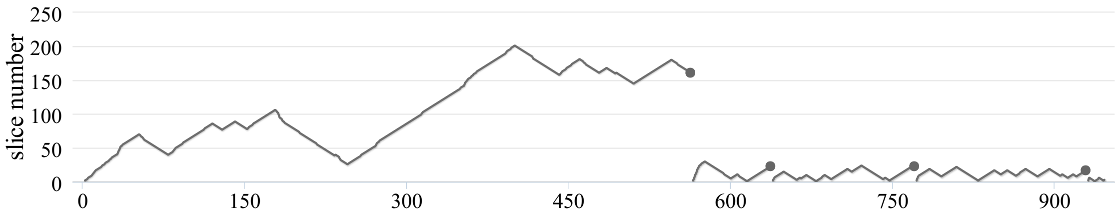
(b)

(b) MRI of bones and joints with 8-129 (series-images).



(c)

(c) CT of the head with 1-125 (series-images).



(d)

(d) CT of bones and joints with 11-582 (series-images).

Figure 4.2 Slice change events during navigation with time equalized. An ascending line indicates the image selector is being slided to the right; a descending line means a movement to the left. The circles indicate a change to a new series of the exam.

Fig. 4.2c, for instance, presents an exam with a single series where the back and forth navigation movement is also recognizable. The same pattern is also recognizable in each one of the four series presented in Fig. 4.2d, particularly in the first one, which is larger than the other three smaller series. The left/right changes in the navigation direction of the image selector are not equivalent. The radiologists tended to slide the image selector to the right more often (53.7%) than to the left (46.3%), i.e., they are more likely to move the image selector towards the end of the series than towards its beginning. We performed a Student's t-test, which demonstrated that this effect occurred with statistical significance ($p = 0.0013$).

Our implementation was based on the centralization of the ODM buffer according to the position of the pivot. The collected results, however, indicate that the ODM strategy would probably be more efficient if its buffer was not centralized, but instead, organized according to the previously mentioned proportions.

4.2.2 On-demand Download Manager

We analyzed the ODM behavior for events with MRI and CT scans. Radiography was excluded from this analysis as it does not contain multiple slices. Each column of Fig. 5 shows an event where the blue part stands for the successful hits and the red corresponds to the access errors in the ODM buffer. The value at the top of the columns is the user satisfaction regarding the waiting time on the slices navigation task, in a 5-point Likert scale where 1 (very slow) and 5 (adequate).

The 60% of users rated the task with the maximum score (5), 35% with score 4 and 5% with score 3. Even those cases with errors in the cache received a good evaluation due to the small waiting time for image transfer. Notice that some exams include more than one body part, e.g. head and spine. They are marked with * in Fig. 4.4. It is also noticeable that the number of views is greater than the number of images of the study, showing that the user sees the same region more than once, as discussed above.

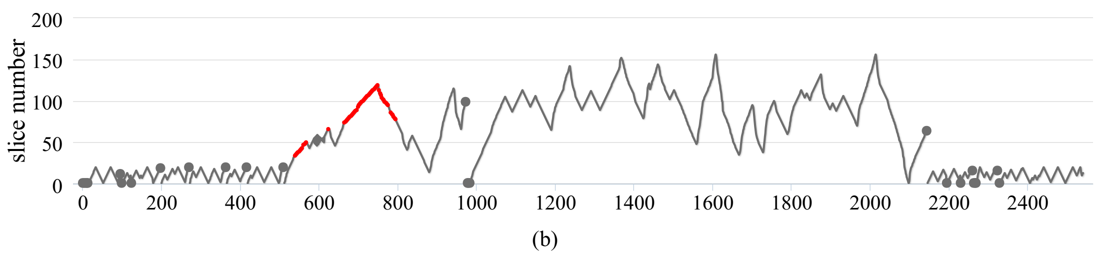


Figure 4.3 Slice change events during navigation with time equalized. The circles indicate a change to a new series of the exam. MRI of the head and angiography with 14-459 (series-images). The regions in red indicate buffer errors.

The average of successful buffer hits for all events was 95.26% ($SD = 5.36$). In Fig.4.3, the buffer error (miss) is caused by another reason. Here, the user advanced the image-selector at a speed greater than the refresh rate of the ODM in a series with many slices.

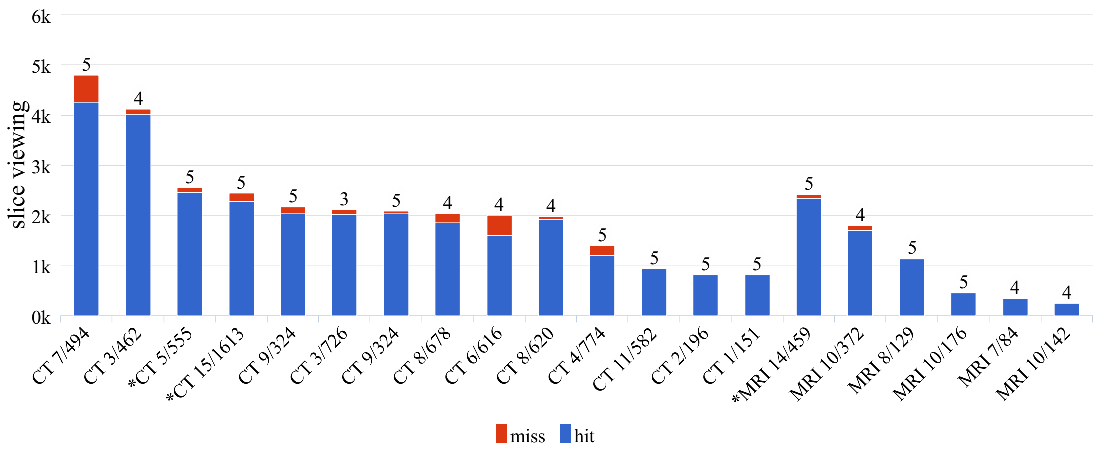


Figure 4.4 Number of slice visualization events with proportion of cache errors and user satisfaction. For each exam, the blue part stands for the successful hits and the red corresponds to the access errors in the ODM buffer. The value at the top of the columns is user satisfaction regarding the waiting time on the slices navigation task, where 5 is best.

It is noticeable that changes in the navigation direction usually occurred within the threshold of the buffer update. This means a visualization without waiting for the user. We also observed that exams with fewer images per series (in average), which are common in emergency cases, presented the best results in terms of cache errors. This also impacted on the perceived user experience. As shown in Fig. 5, exams with larger series tend to present more cache errors and lower user satisfaction regarding the waiting time. In addition, the buffer errors are also sensitive to the type of exam (CT or MRI) and network performance during the experiment (number of connected users, peak hours, etc.). Finally, images with more information (less black areas) generate larger JPEGs, which may affect the general system performance.

To measure the impact of using compressed images in our approach, we evaluated the radiologists' perception of images quality. The results show that 72.1% of the users answered 5 (very good for diagnosis) and 23.3% answered 4, which means the image quality is considered suitable for diagnosis. Grades from 1 to 3 (4.6%) were given only when a significant zoom factor was used during the image visualization or when the image was captured by a low-quality acquisition equipment.

4.3 Discussion

This experiment presented a new approach that provides dynamic optimization for fast medical image transfer and visualization suitable for mobile and stationary devices. Our approach was implemented and validated using a real use case, the application Animati Viewer, which is a web viewer for diagnostic images, part of the Animati PACS.

The ODM plays an important part in the process of controlling how much memory is used by the application. Its internal buffer dictates how many images will be stored in memory, which allows the application to estimate and adjust its memory consumption based on the available resources. As presented in our results, the amount of memory used by our implementation is constant, which is a key aspect to make the approach suitable to run on resource-constrained devices.

Some previous researches work only with uncompressed DICOM files, affecting the access time on networks with low bandwidth (Choudhri and Radvany, 2011; Kaserer, 2013). Our approach, instead, uses compressed JPEG images in the whole process, which saves on network transfer, making the application capable of being used in situations where the connectivity is not ideal, e.g. mobile networks. Even though the compression process might interfere with the original image data, Kim et al. (2011) show that compressed medical images have already been used with good results in a system for rapid emergency care via mobile networks using the JPEG2000 algorithm. We confirmed that, during our tests, by asking the users to evaluate the quality of the images regarding the diagnosis process. In a Likert scale ranging from 1 (poor for diagnosis) to 5 (very good for diagnosis), 72.1% of the users answered 5 and 23.3% answered 4, which means the image quality is considered suitable for diagnosis.

The results are encouraging to support the idea of using compressed images to minimize data transferring without sacrificing medical judgment.

Our experimental protocol with radiologists and 40 different datasets demonstrated that the Animati Viewer, after being equipped with our solution, was able to minimize the amount of information downloaded through the network, without sacrificing the user experience.

5 EXPERIMENT II - MOBILE DIAGNOSIS

The satisfactory performance evaluation of the Animati Viewer obtained in experiment I, motivated us to explore more questions about the medical analysis in mobile devices. So, we started planning face validation experiments especially focused on the ability to perform accurate diagnosis using mobile tools in a clinical environment. Besides other experiments regarding the still incipient use of JPEG-compressed images in diagnostic interpretation. The use of compressed images is widespread in other areas and is a key aspect to keeping the download rate acceptable in environments with limited networking.

Given this context, in this experiment we present a multivariable user study that investigates the diagnostic concordance between image analysis based on mobile interfaces and conventional workstations. This is a major contribution, as the data we used and the experiment conditions are those from a real clinic (unfiltered). A singular aspect of our experiments is that they were applied on a distinct DICOM viewer (Animati Viewer) that uses a combination of client- and server-side procedures to optimize the image transfer and visualization, presented in the **Experiment I**.

Another contribution is that our research covers typical modalities in on-call situations, especially including radiography exams, underexplored for mobile interpretation in previous works. We hypothesize that, for these modalities, the image analysis performed on a mobile interface is not different from the image analysis made on conventional workstations. Moreover, we inquire a list of essential tools for mobile diagnosis, grouped by exam category and body part.

5.1 Methods

We designed our experiments to study the diagnostic concordance between image analysis based on mobile devices and conventional workstations. We performed a between-subject task-analysis using CT, MRI and radiography datasets. Each participant interpreted a set of exams using a tablet device and then ranked the concordance of the obtained report with the analysis made on a standard desktop workstation. Moreover, we investigated the adequacy of the screen size, image quality, usability and the availability of the tools necessary for the analysis.

5.1.1 Experimental Protocol

Eleven radiologists participated as volunteers in our experiment (8 males and 3 females). Eight of them declared themselves experienced and other three are residents currently at the last training stage (fellowship). The group covers several sub-specialties in radiology, e.g. neuroradiology, musculoskeletal, abdominal and thoracic. They are active professionals with appointments in more than one clinical centers and/or hospitals, having large experience with PACS systems.

Our research was conducted at the premises of a partner teleradiology center, with standardized real radiology environmental conditions, such as reduced lighting and sound. Another adopted procedure was transferring the images at the time of interpretation, as usual in real-world conditions.

The protocol for our experiment was based on the following steps, assuming that the main task is to perform the diagnostic analysis of the exam and perform annotation using a mobile viewer.

Step 1, Assignment. The studies/images are assigned to the participants according to their radiology specialty. It occurred in a blind process and special care was applied to ensure a matching between the exam and the radiologists reading capabilities, e.g. head exams should be addressed by neuroradiologists.

Step 2, Mobile analysis. Radiologist reads the exam using the mobile device.

Step 3, Standard procedure. Radiologist reads the exam using a conventional medical image workstation.

Step 4, after each visualization process (after step 3) participants answer an image analysis questionnaire evaluating the concordance between the report obtained on the mobile device (step 2) and the one obtained using the standard procedure (step 3). Additionally, participants evaluate other variables correlated with this analysis.

Steps 2 to 4 are repeated until the participant completes a pre-defined number of analyses. Finally, there is a Step 5, where participants answer a workflow questionnaire, with questions regarding the experiment as a whole.

Notice that the same radiologist performs steps 2 and 3 in sequence for the same dataset, which places a bias in favor of the standard procedure. This means that all major findings are already known when reviewing the images a second time. However, it does not impact our goal of measuring diagnosis concordance, as we assume the standard workstation analysis is the most accurate and any discordance can only depreciate the mobile analysis.

5.1.2 Studies Selection

We focused our experiment on emergency exams. The reason is that mobile viewing is particularly useful in emergency, as it allows for rapid access to images through the network, which enables early assessment and treatment for the patient.

Initially, we set up a list with the number of studies per modality and body part that would be used in the experiment. We selected a set of CT, MRI and radiography studies that were proportional to the historical number that such cases appear in the partner clinic. These modalities are based on on-call conditions, so as a consequence more radiographs of bones were listed than MRI of spine.

Following step 1 of the protocol, before each experiment task, we established which exam in the predefined list was more compatible with the participant's worklist, assigning such exam for the analysis. This process ensured that radiologists performed the task on images of their specialty.

Exams with multiple acquisition protocols, non-contrast- enhanced and contrast-enhanced were used. Besides the images, radiologists also had access to patient clinical history when available.

5.1.3 Hardware and Software

The mobile analysis software adopted for the present experiment was the Animati Viewer, which is describe with more detail in the previous chapter. The viewer uses a combination of client and server-side procedures to dynamically optimize the data flow for fast image transfer and visualization on mobile devices. This feature is crucial to the validity of our experiments as this specific orchestration of methods allows the image viewer to be reliable on resource-constrained environments, such as those with low network bandwidth or little available memory. Moreover, due to the limited screen size in most mobile devices, the viewer does not allow simultaneous multiplanar view.

The mobile device selected for our experiment was an Apple iPad mini 3 with 7.9 inches. This equipment has been chosen for presenting a satisfactory performance in previous works on mobile diagnostic. Besides, it provides a resolution of 324 pixels per inch (a total of 1536 x $2048 pixels$) and luminance of 394 cd/m2, which is in accordance with American College of Radiology (ACR) recommendations for studies such as those used in our experiment (NORWECK et al., 2013).

For the final desktop diagnosis, the participants used the standard workstation equipped with monitors that satisfy the requirements for digital medical images visualization, with 27 inches, Full HD resolution and 350 cd/m2 of luminance (PIANYKH, 2008). Each user has chosen their preferred software for the analysis. Available options were the Animati PACS workstation and OsiriX imaging viewer. Fig. G.1 depicts a radiologist performing diagnosis on a mobile and on a desktop. In the foreground of the image, a user is analyzing an angiography CT slice with the mobile application. This viewer provides usual tools for diagnostic analysis, such as windowing, navigation through slices (scrolling), transformations (zoom, move and rotate), measurement lines and angles, among others, all adapted to the touch-based mobile environment. We highlight the easiness of using this interface with widely known multitouch gestures. For instance, using the pinch and slide gesture, the user can quickly change the image size and pan it to the ideal position.

5.1.4 Data Acquisition

Data was captured qualitatively through three different questionnaires. Initially, the user is invited to answer a characterization questionnaire with information concerning professional experience, radiology subspecialty, main activity institution and previous experience with mobile applications.

After each study, the participant answers the image analysis questionnaire with questions regarding the diagnosis task that has just been performed. The goal of this survey is to better understand the particular elements of each exam. It inquires about the concordance between the findings obtained on mobile and desktop devices, as well as variables that can help to explain any possible discrepancies between these reports, e.g. image quality and size, ease of use, diagnostic confidence and necessary tools that were not available in the mobile environment.

After finishing all the assigned studies, the participant answers a workflow questionnaire. This questionnaire aims to explore the situations in which the mobile application may be more useful in the medical workflow. Moreover, it aims at measuring the importance of radiologists having access to PACS systems outside of their working environments, how a mobile interface favors collaborative discussion with colleagues, and the advantages of mobility for emergency cases and other situations where quick access is necessary.

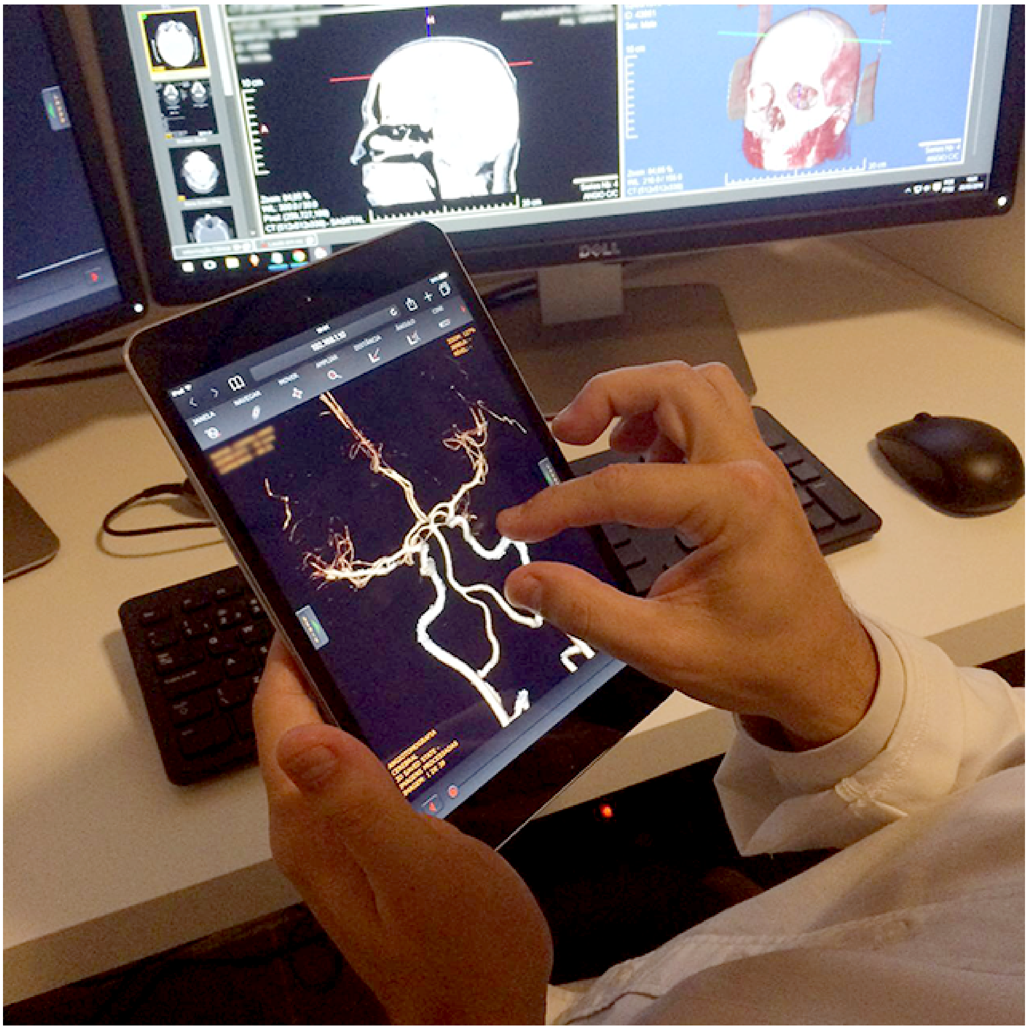


Figure 5.1 A user handling the mobile application during the experiment. In the foreground the Animati DICOM Viewer. In the background a conventional PACS workstation.

In the workflow questionnaire, we also performed an evaluation of the interface usability based on the System Usability Scale (SUS) (BROOKE et al., 1996). With the exception of the clinical concordance, which considers the interpretation obtained on the desktop, all other questions refer to the experience using the mobile interface.

5.1.5 Metrics

5.1.5.1 Clinical concordance issues

With the image analysis questionnaire, we primarily evaluate the clinical concordance between annotations made with the mobile investigation and the diagnosis report made on a standard workstation. As previously described, the user answers such questionnaire shortly after making the definitive report in the conventional environment.

Both the mobile and the workstation reports were produced by the same user. This decision adds a bias as discussed in Sec. 5.1.1, but it has two major advantages. First, it eliminates one variable of the experiment. Secondly, it allows focusing on the objective of establishing the differences between the two platforms avoiding issues that would rise if radiologists' capability was unwantedly compared.

To measure the concordance between the diagnoses, we applied an adaptation of the American College of Radiology RADPEER system, a medical disagreements metrics (JACKSON et al., 2009; MELVIN et al., 2004). This metric allows distinguishing the clinical judgments between two reports on a scale from 1 to 4, as presented in table 5.1.

Table 5.1 The 4-point rating scale of adapted RADPEER scoring system.

1	**COMPLETE CONCORDANCE:** full agreement with the report's content.
2	**ALMOST COMPLETE CONCORDANCE:** discordance on change difficult to identify (easily lost), but without clinical significance.
3	**PARTIAL CONCORDANCE:** Discordance in change easily identified, but no clinical significance.
4	**DISCORDANCE:** Discordance on change that should have been identified and described, with clinical significance.

The first option is the Complete Concordance, in which findings obtained in the mobile environment were exactly the same as the conventional interpretation. Following, the Almost Complete Concordance is employed in events where there was a discrepancy in a feature difficult to identify (easily lost), but without clinical significance. This discrepancy category is an acceptable on-call conditions, considering that secondary findings may be revised later.

Item three is the Partial Concordance, where the participant has lost an easily identifiable structure, but without clinical significance. Finally, there is a Discordance when findings that should have been identified on the mobile device were only noticed using the standard workstation. This case may impact on the patient healthcare. Additionally, for each diagnostic event, we monitored other four variables using five-point Likert scale: ease of use (very difficult to very easy), diagnostic confidence (no confidence to high confidence), image quality (very bad to excellent) and size (very small to appropriate).

Other more factual data were also collected during the experiment, e.g. technical problems such as network outage, uncharged battery, application closing unexpectedly, missing tools for analysis of the study. The identification of a minimal set of tools necessary for each type of analysis is essential to discuss the discordance cases and to improve the interface.

5.1.5.2 Usability

We evaluated the mobile application usability using the previously mentioned SUS questionnaire (BROOKE et al., 1996). This widely used method presents a balance between being scientifically accurate and not being excessively long for the user and researcher. It has been used to evaluate products, services, hardware, websites and software applications. It partitions the overall quality of an interface in terms of effectiveness, efficiency and satisfaction. The metric consists of ten questions that are answered in a 1 to 5 scale, where 1 means "Strongly Disagree" and 5 means "Strongly Agree".

5.1.5.3 Post experiment review stage

After the whole experimental process and data collection, we reviewed all cases in order to identify the main findings of each exam and classify them into groups according to the body part and modality.

An expert radiologist with 14 years of experience reviewed all events presenting any discordance. Both the questionnaire responses and the original study images were overviewed to collect arguments that could explain the diagnostic divergence.

5.2 Results

We report in this sections results in diagnosis concordance (Sec. Diagnoses Analysis), availability of image analysis tools (Sec. Image Analysis Tools) and interface usability (Sec. Usability).

Body region	Diagnosis	Nº Cases	Nº Diagnosis
CT Abdomen and Thorax (8 cases)	Peritoneal effusion (2), Intestinal obstruction (2), Normal (1), Liver neoplasia (1), Pancreatic cysts (1), Acute appendicitis (1), Liver cyst (1), Renal lithiasis (1), Ovarian cyst (1), Colonic diverticulosis (1), Pulmonary nodule (1), Atelectasis (1), Ground-glass opacities (1), Pulmonary emphysema (1), Pulmonary calcifications (1)	8	17
CT Bones, Joints and Spine (5 cases)	Degenerative changes (2), Crystal arthropathy (1), Bone fractures (1), Normal (2), Intraosseous haemangioma (1)	5	7
CT Head (10 cases)	Normal (4), Infart (1), Encephalomalacia (1), Intracranial calcifications (1), Subgaleal hematoma (1), Benign neoplasm (1), Small vessel disease (2), Cerebral calcifications (1), Deviated septum (1), Maxillary retention cyst (1)	10	14
MRI Bones, Joints and Spine (5 cases)	Tendinopathy (1), Tendon rupture (1), degenerative changes (3), Tenosynovitis (1), Adhesive capsulitis (1), Rupture of the anterior cruciate ligament (1), Meniscal rupture (2), Joint effusion (2), Normal (1), Disc Herniation (1)	5	14
MRI Head (5 cases)	Infart (1), Small vessel disease (1), Aneurism (1), Normal (2), Malignant neoplasia (1)	5	6
Radiographs Bones and Joints (17 cases)	Normal (8), Osteomyelitis (1), Arthroplasty (1), Joint effusion (1), Degenerative changes (4), Crystal arthropathy (1), Bone fractures (1), Post surgical changes (2), Osgood-Schlatter disease (1)	17	20
Radiographs Head (3 cases)	Normal (3)	3	3
Radiographs Thorax and Abdomen (11 cases)	Normal (4), Consolidation (1), Pleural effusion (1), Bronchitis (2), Post surgical changes (2), Interstitial disease (1), Mild bowel distension (1)	11	12
Total		**64**	**93**

Figure 5.2 Range of cases interpreted in our experiment. The main diagnosis (the one related to the reason that motivated the exam) in each category were grouped in the post-experiment review.

5.2.1 Diagnoses Analysis

Figure 5.2 lists the resulting diagnoses from the exams interpreted in our experiment. The organization by modality and body part is inspired by a related work presented by John et al. (2012) . A total of 64 studies with 93 main diagnoses were analyzed, assuming that any single exam can contain several diagnoses. The main diagnosis is commonly related to the reason that motivated the exam. Nevertheless, a study may have secondary findings that were not included in this list.

In our research the exams were not pre-defined. They were selected in order of arrival at the partner clinic. As a consequence, our experiment presents a higher diagnostic variance than in the previous works. The number of cases in each category reflects the flow of emergency exams in the teleradiology section where the study was performed.

As concordance was quantified in levels using the RADPEER system (see Sec. 5.1.5.1) instead of a binary discordant/concordant value, no statistical significance analysis is provided.

Fig. 5.3 shows the concordance count between mobile and conventional diagnostic analysis grouped by modality and body part. Our results showed that 56 cases were classified with complete concordance (87.69%), 5 cases with almost complete concordance (7.69%) and 1 case (1.56%) with partial concordance. Only 2 studies presented discordance between the reports (3.07%).

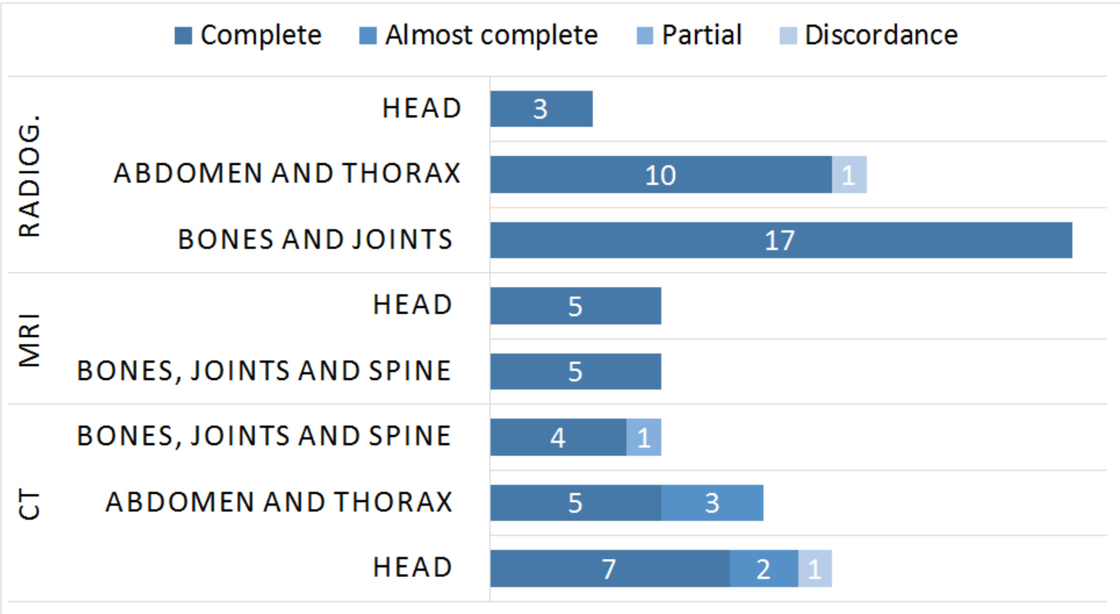


Figure 5.3 Diagnosis concordance. Peer review scores grouped by body part and image modality.

5.2.1.1 Discordances

Regarding the cases with some degree of discordance, only 2 inaccurate interpretations are clinically relevant, both from non-experienced participants. The first one was a radiograph of the abdomen, in which the radiologist did not see **Discretely dilated air-filled small bowel loops on the right iliac fossa** using the mobile device. The participant explained that it is a small structure that is difficult to identify, but still clinically significant in their opinion. They also emphasized that seeing the exam again using the mobile viewer would probably allow identifying the clinical finding. However, at first visualization it did not draw the examiner's attention. During the expert review, this interpretation was considered as not having clinical impact. The expert reviewer would apply the rating 3 (almost complete concordance), i.e. difficult to identify (easily lost), but without clinical significance.

The second case classified with clinical discordance was a head CT exam with only axial images available for the analysis. According to the participant, the interpretation of this specific study requires the measurement of the **Keros classification**, which can be performed only in the sagittal plane. The reviewer radiologist agreed with the participant's response. The study was diagnosed with **Deviated septum and Maxillary retention cyst**. This is an example where disagreement occurred for lack of a multiplanar reconstruction (MPR) tool in the mobile viewer. In addition, the user marked 1 in the confidence scale for this diagnostic (not confident), but rated the image quality and size higher, indicating that the difficulty was caused by lack of MPR post processing.

5.2.1.2 Partial Concordances

A partially discordant case (a structure of easy identification was missed) is also linked to the lack of MPR. The case occurred in a neck CT study, viewed by an experienced neuroradiologist who described it as a difficult case. The radiologist commented that the reason for the discrepancy was the inability to see the images in the sagittal plane and the lack of a multiplanar reformatting tool. Other participants also reported that all the image exams of spine or neck must be viewed in such plane (sagittal). This case was diagnosed as normal, with a maximum score on confidence assessment, screen size and image quality. In discussions with the expert radiologist, he observed that the lack of MPR was determinant for the classification, even if this case has not presented a specific finding. This issue was avoided in previous work with a pre-selection of study cases. Our experiment, instead, allowed us to observe the impact of this limitation in the diagnostic concordance.

5.2.1.3 Almost complete Concordances

Five cases were classified as almost complete concordance, in which the user noticed only a difference difficult to identify and without clinical significance between the desktop and mobile reports. One of them is a thorax CT exam, diagnosed with a **Lung nodule**. The radiologist explained that the variation was a **Small nodular thickening in the lingula, suggestive of intrapulmonary lymph node**. Image size and quality and diagnostic confidence were classified on the scale 4. Besides, no tool for the imaging analysis was missed. Even in the revision stage, the main reason for this discrepancy was unclear. It has apparently been induced by a second visualization in a more common user environment (OsiriX software in this event).

Other two cases with the same level of discordance have occurred in a CT of the upper abdomen and CT of the pelvis. In these events, the radiologist missed the MPR tool. They explained that exams with complex diagnosis, including more than six significant clinical findings would benefit of multiple views. The screen quality and size were classified in scales 4 and 3, respectively. In the conference with the reviewer radiologist, we concluded that those are complex cases to be analyzed even on the conventional workstations. Features such as small screen and lack of advanced visualization tools have made the diagnosis more difficult to perform with impact in the final result.

Finally, two head CT studies were also classified as almost complete concordance.

Table 5.2 Count of missing tools grouped by modality and body part. Parentheses indicate the number of radiologists that mentioned the specified missing tool.

Modality	Body region	Missing tools
CT	Head	MPR (4)
	Abdomen and Thorax	MPR (4)
	Bones, Joints and Spine	2 Views (2), MPR (1)
MRI	Head	2 Views (1)
	Bones, Joints and Spine	2 Views (2)
Radiographs	Head	–
	Abdomen and Thorax	2 Views (2)
	Bones and Joints	2 Views (2)

The first one, diagnosed with **Encephalomalacia** and **Intracranial calcifications**, the patient presented other factors, such as HIV positive. So, the radiologist suggested additional correlations to complete the report. In this case, when viewing the images on the workstation, the doctor noticed a **Volumetric reduction of the middle cerebral peduncle**. According to him, this was caused by viewing the exam again. The participant did not point out any missing tool and rated high values for ease of use (5), size (4), image quality (4) and confidence (5). The second case happened with a participant in the final training stage, where the diagnosis was **Small vessel disease**. In this task, the user was very insecure for not having the MPR tool, and consequently, ranked confidence as 1 (not confident). They nonetheless could not specify a difference between reports. The lack of tools for image assessment on other planes was more frequent in events with less experienced users.

When analyzing radiography tasks separately, only 1 out of 31 cases was classified as discordant. However, this classification was challenged in the review stage. It is important to stress that all other 30 cases had complete agreement of the diagnostic analysis obtained on the mobile device when compared with the desktop report.

5.2.2 Image Analysis Tools

Table 5.2 lists the tools that users have reported as missing during the experiments. This table is grouped by modality and body region. In CT scans, especially head (4 cases), followed by the thorax and abdomen (4 cases), the main tool that users have missed was the multiplanar reconstruction (MPR). As the experiment was performed in a teleradiology section, image acquisition is performed in many different clinical labs that use distinct protocols. For some cases, the images are transmitted only in the axial plane. Thus, a multiplanar reconstruction may be required for analysis in the sagittal, axial or coronal planes. For example, for column and neck, it is necessary to view the images in the sagittal plane to obtain a better spatial perception of the vertebrae. Consequently, column studies without images in the sagittal plane were more difficult to diagnose using the mobile viewer.

According to an experienced participant, another important case for the MPR tool are emergency situations where the patient can not lay in the ideal position for the images acquisition. In such cases, this tool is often used in the workstation to adjust the angle and generate a new image. A solution to integrate MPR in the viewer is discussed in the next section.

Another tool participants missed was the possibility to display an image grid, with two or more images side by side. Due to screen size issues, the interface design of the mobile viewer used in the experiment allowed the visualization of a single, which fills all space available. In 4 cases with radiography exams, the participants reported that they would like to use this feature, explaining that it is common for this modality the visualization of two images at the same time for comparison. The lack of this tool has also been noticed when analyzing a spine CT scan. The participant needed to compare the series in two different planes. The same happened for 3 head and musculoskeletal MRI exams. Contrary to the MPR, the absence of image grid had no direct impact on the concordance of the reports.

Interestingly, less experienced participants that interpreted CT scans pointed the need for an MPR tool in their answers. These results might indicate that the newest generation of physicians tends to need more tools for a confident interpretation

5.2.3 Usability

The overall average of SUS questionnaire in our analyses was 91 points (min: 82.2, max: 100, sd: 5.55). The 10 answers are converted to a single number representing a composite measure of the overall usability. Each item contribution will range from 0 to 4 (score is inverted for negative statements) and the sum of scores is multiplied by 2.5 to obtain the overall SUS score. Fig. 3 shows the distribution points (y-axis) for each user who completed the experiment (x-axis). Comparatively, this result is significantly higher than the average value of 68 obtained from another SUS-based analysis performed on 500 interfaces, including products, services, hardware, software, websites and applications[1]. Moreover, according to surveys that compare SUS scores for different systems, an average score of 91 receives a grade **A** and is considered an "Excellent" system (BANGOR; KORTUM; MILLER, 2009; BROOKE, 2013).

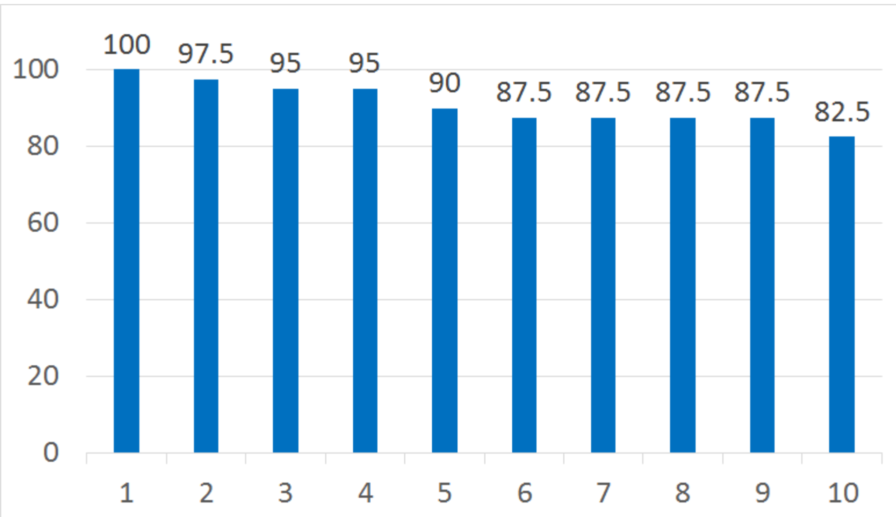


Figure 5.4 SUS scores for each user.

[1]Measuring usability with the SUS (http://www.measuringu.com/sus.php)

5.3 Discussion

Firstly, and like previous works (JOHN et al., 2012; MC LAUGHLIN et al., 2012; BHATIA et al., 2013), our results showed that a mobile viewer can properly display CT and MRI sequences for diagnosis procedures. Our results have further shown that this leads to diagnosis results that are highly concordant to those obtained in desktop workstations. In the previous section, we discussed the reasons for the high concordance and the few discordant cases.

Despite the growing popularity of new imaging techniques, x-ray radiographs are still widely applied in emergency situations. They are a low-cost solution that is sufficient to display evident structural alterations, providing medical personnel with an agile tool to make decisions. We analyzed the mobile concordance of radiograph diagnosis for the first time, which also demonstrated to be highly positive. Our results highlight the role of mobile tools in radiology as being a key component to allow the access of PACS features outside the radiologist workplace. As demonstrated by the results of our questionnaires, remote access was pointed as a very important functionality by 70% of the participants.

Regarding important features of a mobile device for the diagnosis process, among the variables measured and under the circumstances of our experiment, screen size and image quality had no direct impact on the diagnosis. Specifically about image quality, the mobile viewer used in the experiment applied an approach that combines lossless and lossy images to rapidly download patient information, which is helpful for clinical decisions. As our results demonstrate, such approach did not affect the participants workflow, since questionnaires detected no or minimal problems while performing the diagnosis as a consequence of image quality. This feature of a mobile viewer strengthens the previous results by Kim et al. (2011), which show that compressed images provided a fast transmission while maintaining enough quality for diagnosis on a portable device via mobile networks.

Our analysis also detected some usability issues caused by different sources, e.g. network problems, missing tools in the viewer and discrepancies between user expectations and how the mobile viewer behaved. Those issues are rather related to system architecture than user interface design. For instance, participants complained about multiplanar reconstructions, which were missing in the mobile version and were pointed out as an important element to some types of diagnosis. We envision three alternatives to overcome such limitation. The first one is to standardize how images are delivered to the partner clinic, ensuring that all exams would be transferred in the necessary plans. The second one is to enhance the mobile viewer, adding a server-side module able to make reconstructions on-demand, which would be transferred to the mobile viewer. It would transparently provide users with the required information despite it not being originally present when the original scan was delivered to the clinic. Finally, the third option is to deploy an advanced image processing engine for mobile devices to process multiplanar and volumetric reconstruction for any tomographic exam from the PACS database locally on the device, eliminating any server-side reconstruction step.

6 EXPERIMENT III - MEDICAL IMAGING VR

In the **Experiment II**, we applied a preliminary survey with 10 radiologists investigating the importance of 3D volumetric reconstructions in the medical workflow. All participants marked the diagnostic option (100%), but only for specific cases such as to identify fractures. Other areas have also been mentioned, including planning surgeries (90%), educational presentations / classes (70%), operating room, patients appointments and discussion with colleagues (60%). In the same survey, we asked the participants how much interest they have in the introduction of new technologies in their workflow, and 100% answered in the maximum range of interest (very interested).

These results motivated us to design another experiment to verify if immersive 3D visualization can aid in imaging diagnosis process. The experimental setup, results and discussion are present in this chapter.

The development is focused on two key elements: the first premise is based on the communication between radiologists and referring physicians (e.g. surgeons, cardiologists and orthopedists). As shown by (ROSENKRANTZ et al., 2016), 80% to 90% of referrers agree that the discussion between these professionals improved their understanding of the radiology report, affected patient management, and enhanced radiologists' role. However, as a consequence of an ever increasing use of teleradiology, the radiologists began working remotely (outside of the clinics and hospitals). Thus, their contact with physicians and patients was subsequently reduced (GLAZER; RUIZ-WIBBELSMANN, 2011). The second premise is that in most cases the physicians have only the report and raw images which are poorly comprehensive. Such doctors have knowledge of the patient's clinical case but dissociated from the imaging result.

We designed this experiment aiming to explore the knowledge of expert professionals in digital medical imaging: radiologists and medical physicists, thus gathering technical feedback over our approach and about the current application of VR technology in the medical context.

6.1 Methods

In order to measure the capabilities of VR in the diagnostic procedure of fracture identification, we performed a between-subject task-analysis using two CT-scan datasets. Each subject, wearing a head-mounted display and using a couple of interaction tools (windowing and zoom), tried to find fractures in one of the studies. We monitored four dependent variables: the diagnostic effectiveness, 3D images quality, ease of interaction and cybersickness.

6.1.1 System Design

We have developed an engine able to apply multiplanar and volumetric reconstructions in tomographic imaging, like CT and MRI sequences. The system has been designed using the Unity platform and parallel GPU processing.

The Unity platform[1], originally intended for usage with game development, provides several advantages. The most important one, which drove our development was the support for both desktop and mobile devices (smartphones and tablets). It also provides WebGL support and allows the use of multiplatform shaders.

One limitation with this platform, however, is the lack of proper support for 3D textures for the volume. It is possible to create them but it is not possible to update their data without refreshing the entire texture at once, which causes it to reach memory limits in mobile devices. It forced us to create a solution based on the use of 2D textures only.

In order to provide the images to the engine application, we developed an algorithm that runs on the server computer and packages all DICOM slices from an exam into a specific lossless file format. This pre-processing occurs on the picture archiving and communication system (PACS) context - server side - and takes advantage of having all the image data available at the time.

This server algorithm was designed to make a file with the maximum dimensions (4096x4096 pixels) and bits-per-pixel (32bits) supported by most platforms. Thus it is possible to pack many tomographic images - slices - into fewer files. Once the files are generated by the server, they are downloaded by the client application and loaded as regular textures on the device's GPU. A specialized shader decodes the images in runtime with minimal impact, translating the files back into multiple slices. Such slices can be manipulated and used as the basis for regular volumetric visualizations as well as other more traditional visualization methods. For the medical images 3D rendering we use a generic ray tracing algorithm adapted to our emulated textures and optimized to run on mobile devices.

The PACS system used in the project offers an image viewer compatible with web and mobile interfaces. It is shown on the left of Fig. 6.1 and presented with architectural details in previous chapters. We added the 3D VR action (button displayed on top of Fig. 6.1) to the interface. It starts the visualization engine and triggers the medical image transfer from the server to the device (smartphone, tablet and desktop). The pictures of Fig. 6.1 show the 3D volume rendered by the engine application onto a smartphone.

The visualization engine runs on multiple possible devices. It can be used with a smartphone adapted as an HMD using Google Cardboard or other off-the-shelf or 3D printed mobile HMDs. Alternatively, it can run on a desktop environment attached to an Oculus Rift and a clicker. Both platforms allow rotations, translations and windowing (i.e. to select the density corresponding to bone or soft tissue) in the reconstructed volume. A simple switch action, such as a click on a joystick or a trigger on the HMD, allow navigating through the visualization options.

Figure 6.2 shows an example sequence of actions applied to our interface. $T0$ is the initial state in which the 3D volume is displayed in the center of the screen with standard windowing and position. On $T1$ a joystick trigger is performed to activate the windowing adjustment tool, displaying the two bars with width and center values that are changed by moving the analog stick in four directions. The result of this change is observed in the second image, highlighting the range of bone rather than soft tissue. The picture on

[1]Unity Game Engine - https://unity3d.com

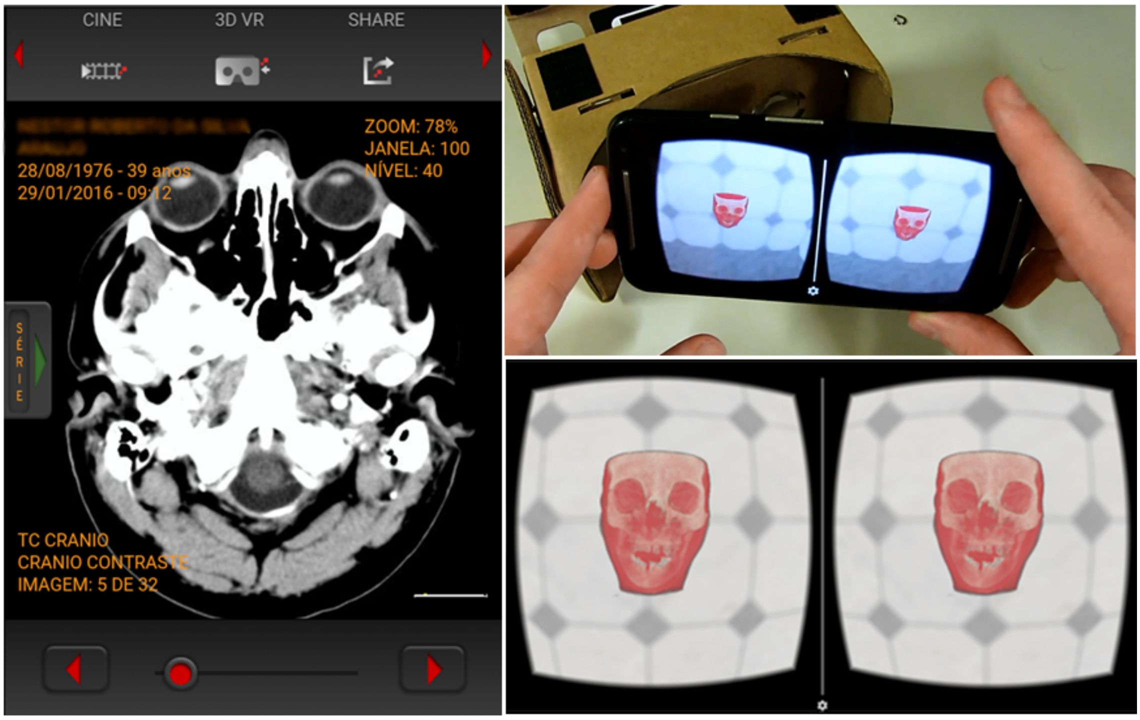


Figure 6.1 Integration of the VR interface with PACS. A 3D VR button is shown at the top of the left image. It triggers the 3D VR engine. On the right, we show a use case with a smartphone-based low-cost HMD displaying the volume reconstructed.

$T2$ represents the user's head movement, which causes a rotation around the object. This natural head movement can be performed until a position of interest is reached. Finally, on time $T3$, a switch action is triggered again, this time enabling the zoom tool. This tool changes the distance to the object using the analog button movement, to focus on a bone fracture for instance.

6.1.2 Studies Selection and Analysis

We selected two specific exams for our analysis. The exams have been searched in the partner clinic's database with the strings: *comminuted fractures*, *bone fracture* and *polytrauma*. Head CT studies appeared as a convenient choice as they are common in routine examination of trauma situations. Moreover, they are suitable for analysis by any radiologist, regardless of specialty.

The two head CT studies with the highest number of fractures were selected and anonymized. The first one (a) with 191 slices, thickness 1mm and bone filter applied in the acquisition. The second dataset (b) has 231 slices and the same thickness of the first.

We conducted a preliminary interpretation to identify existing fractures in each dataset. This analysis was performed by three neuroradiologists from 5 to 10 years of experience. Clinical findings were obtained by viewing images in the conventional way (i.e desktop computer and 2D monitor), using slices in the axial, sagittal and coronal planes, in conjunction with the 3D volume.

The specialists identified seven fractures in the dataset a and six in the dataset b. Doctors emphasized that some of these fractures are internal and small, hardly interpreted

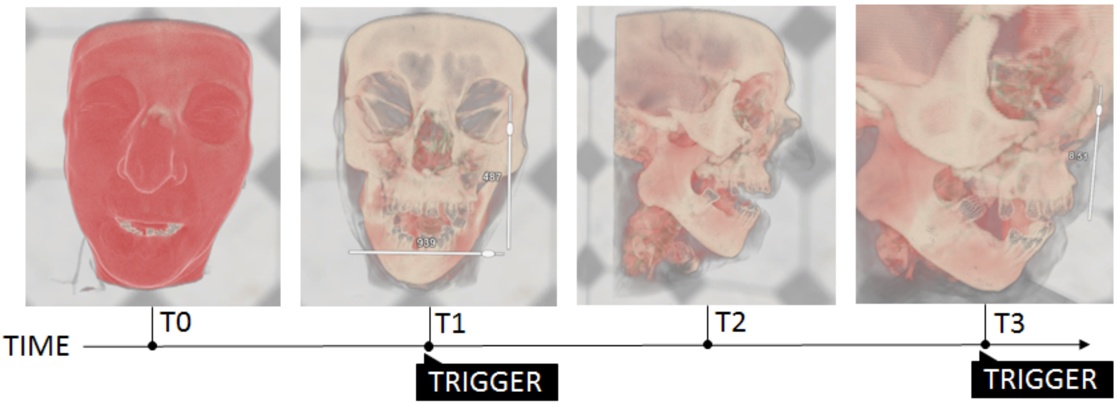


Figure 6.2 A typical timeline of user actions with the interface. $T0$ shows a centered initial position and windowing in tissue range. At $T1$, the windowing tool is activated through a click and the parameters are set to highlight bones. $T2$ shows the volume rotated due to a head movement. At $T3$, the zoom tool is activated to provide details on a specific region.

only viewing the 3D volume as they may be occluded by structures near the surface.

After the studies interpretation, we create two lists with the clinical findings of each dataset. In each list, we included two additional fractures that do not exist to provide false alternatives. In some of them, we simply reversed the laterality of fracture. In other cases, false alternatives pointed to non-existing fractures in locations near existing ones.

6.1.3 Experimental Setup

Fifteen radiologists and one medical physicist participated voluntarily in the study (thirteen males and three females). Their times of experience ranged from 1 to 5 years (56.3%), 5 to 10 (25%) and over 10 years (18.8%). The subjects have subspecialties in radiology. The 33.3% are members of the neuroradiology team, followed by 26.7% of specialists in abdominal radiology, 26.7% in musculoskeletal, 6.7% in thoracic and 6.7% other in specialties. This study was the first experience with virtual reality for 81.3% of participants.

The main user task in our experiment is to find fractures in a reconstructed 3D volume in a virtual environment by applying transformations (such as zoom and rotation) and windowing adjustment. No additional clinical information or viewing in 2D plans were available. Furthermore, no cutting planes were allowed in this version of the interface.

Initially, each participant signed a legal term of consent informing about the compliance with ethical precepts and the details of the experimental protocol. Before starting the experiment all the subjects fill out a characterization questionnaire. The following step is an interface learning session in which a video demonstrating the use of the application and methods of interaction with the HMD and joystick is presented. No preliminary training is allowed.

For this experiment, we chose to use the Oculus Rift DK2 attached to a desktop computer. This choice has been motivated by the wider availability of the device, which can be useful for comparison by other researchers, and due to the device specifications, e.g. higher resolution and performance when compared with Google Cardboard interface. The resolution displayed to each eye by the Oculus Rift DK2 is 960 x 1080 pixels, refresh rate (75Hz), field of view (100).

After the learning session, the user performs the task of finding fractures in one dataset for 2 to 5 minutes according to their preference. Eight users viewed the dataset a and the other 8 analyzed dataset b. Figure G.2 shows an overview of task performance, notice that all subjects conducted the experiment upright. Pictures from left exhibit the joystick interaction for selecting different image densities and enhance important structures, as bone or tissues. Additionally, the figures on right show the head rotations to look for a target position in the 3D volume.

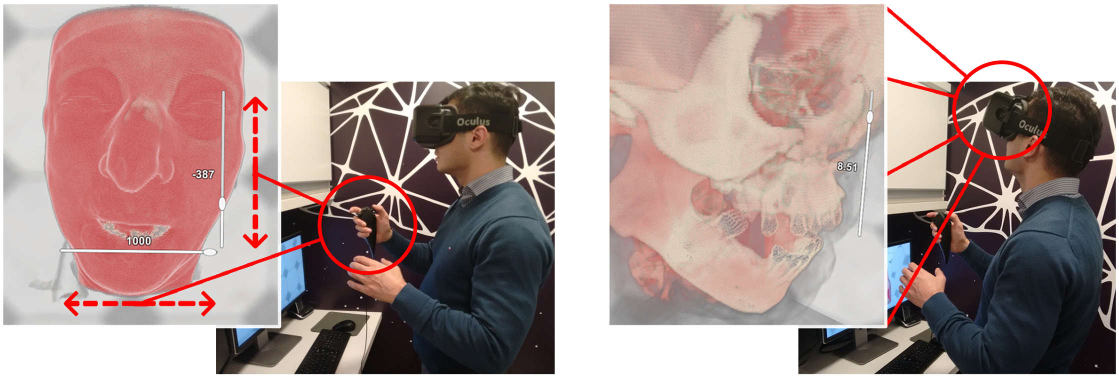


Figure 6.3 A user interacting with a 3D dataset through our VR interface. On the left, he changes the contrast for soft tissues using a handheld analog joystick. On the right, he highlights the bonny structures and focuses on a specific region with natural head rotations. A supplementary video (avaliable at https://youtu.be/5TlwMYVJqPI) to this experiment better demonstrate operation of the interface.

Finally, subjects fill a post-questionnaire with questions about the list of possible fractures found, ease of interaction and comfort during the task. For the comfort analysis, we adapted the Simulator Sickness Questionnaire(SSQ) (KENNEDY et al., 1993), using the questions most related to our case (See Appendix F). The list of possible fractures has been defined in the preliminary interpretation with true and false alternatives. Participants can select as many alternatives as they wish.

6.2 Results and Discussion

We conducted user tests on two selected head CT exams and measured the users' performance in identifying fractures, the subjective quality of the reconstructions and subjective comfort/discomfort.

6.2.1 Diagnostic Effectiveness

Figs. 6.4 and 6.5 show the number of responses on each of the possible observations on to the datasets a and b respectively. The options with marker $*$ represent the false alternatives and the maximum number of answers by alternative is eight.

The first exam has 7 correct answers and 2 false, as illustrated in Fig. 6.4. Regarding the correct options, the lateral right orbit wall and right orbit floor were correctly interpreted by 7 radiologists (87.5%). The right zygomatic arch by 5 radiologists (62.5%), the nasal bones 4 (50%) and maxillary sinus walls 3 (37.5%). The left orbit floor and Le Fort type I had a single vote each. *Le Fort* indicates fractures of the midface, which collectively involve separation of all or a portion of the midface from the skull base (RHEA;

NOVELLINE, 2005). It is a more specific classification of neuroradiology and not commonly used by other areas. Notice that for the dataset a, all true fractures were identified by at least one radiologist.

The answers to the two false alternatives are also shown in the chart of Fig. 6.4. No subject marked the left zygomatic arch (100% hit), because this fracture was on the right side and VR viewing had no impact on the correctness of laterality. Mandible (jawbone) ramus had one wrong vote made by only participant that is a medical physicist, who is not expected to succeed in identifying fractures.

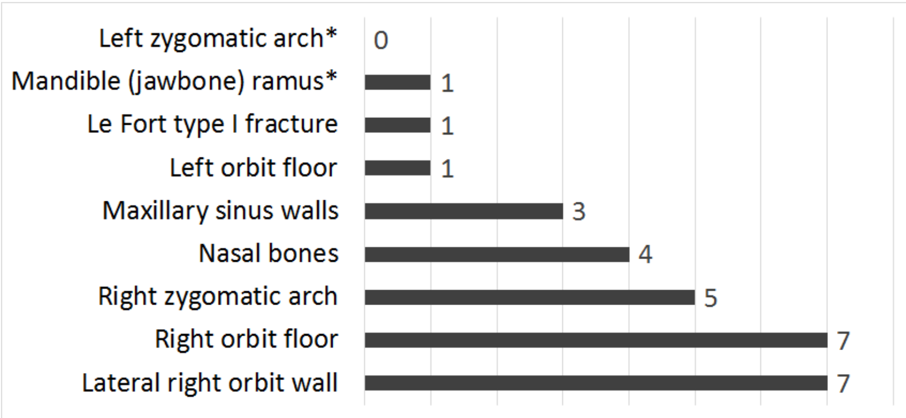


Figure 6.4 Diagnostic effectiveness for dataset a. Possible fractures are in the y-axis. The x-axis shows the number of users that have marked each possible option. The $*$ indicates that the respective bar represents a non-existent fracture (false option).

Fig. 6.5 shows the answers about the second exam with six correct alternatives and two false ones. Depressed right anterior maxillary sinus wall was interpreted by all radiologists (100% hit). Then, the right zygomatic arch and depressed right anterior frontal sinus wall received 7 votes each (87.5% hit). The posterior maxillary sinus wall, which is an internal structure scored only two votes (25%) and other 2 correct fractures in internal structures have no vote. This was expected, as the ethmoidal cells, posterior frontal sinus wall and posterior maxillary sinus wall are head internal structures, hardly seen without making cuts in the 3D volume or viewing on 2D slices. In the preliminary interpretation, the radiologists pointed this explicit limitation of our method and these results demonstrate that.

Similarly to the first exam, the dataset b scored only one vote in one of the false alternatives, applied to bone nasal left, and none in the other. The exam presents facial polytrauma affecting nearby structures. This seem to have taken a participant to precipitate (rather a memory effect than perception). The lateral left orbit wall had no marking, as expected.

As we hypothesized, these results showed a high accuracy rate identifying superficial fractures in both 3D rendered studies. The outer skull fractures in zygomatic arch, anterior maxillary sinus wall and lateral orbit wall, for instance, were found by most radiologists regardless of experience and specialty. Our results also showed the limitation for identification of the internal fractures because they are occluded by surface elements. Thus, we emphasize the application diagnostic effectiveness even though it was the first contact of the subjects with an immersive VR system.

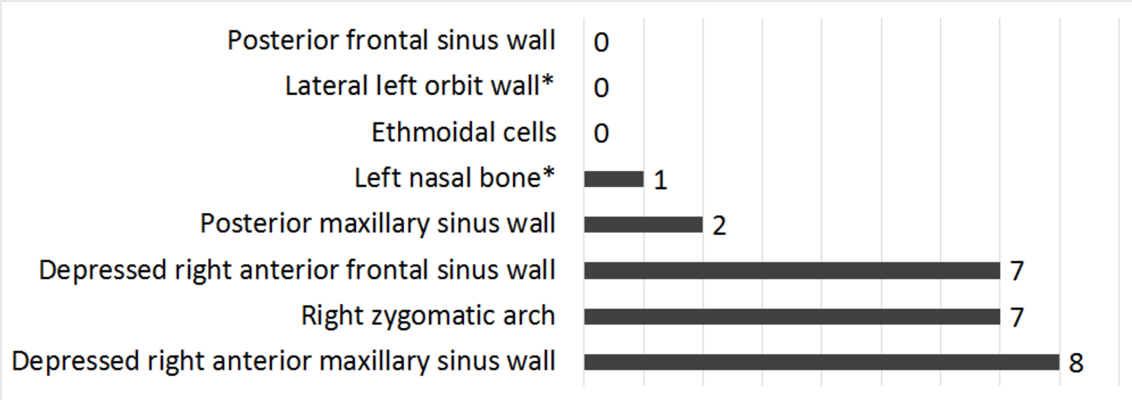


Figure 6.5 Diagnostic effectiveness for dataset b. Possible fractures are in the y-axis. The x-axis shows the number of users that have marked each possible option. The $*$ indicates that the respective bar represents a non-existent fracture (false option).

6.2.2 Usability and Quality

We analyze also two variables related to our interface: ease of interaction and quality of 3D reconstructions. The subjects graded the easiness of interacting using our interface compared to other interfaces for 3D data they are familiar with, e.g. their conventional workstations where mouse and keyboard are used to apply transformations in volumetric images. They also graded the quality of the 3D reconstructions in comparison with the conventional volumetric images, which most often are preprocessed on the acquisition equipment and then sent as 2D images for the radiologists. The responses were collected in a five points Likert Scale questionnaire, from 1 (very low) to 5 (very high).

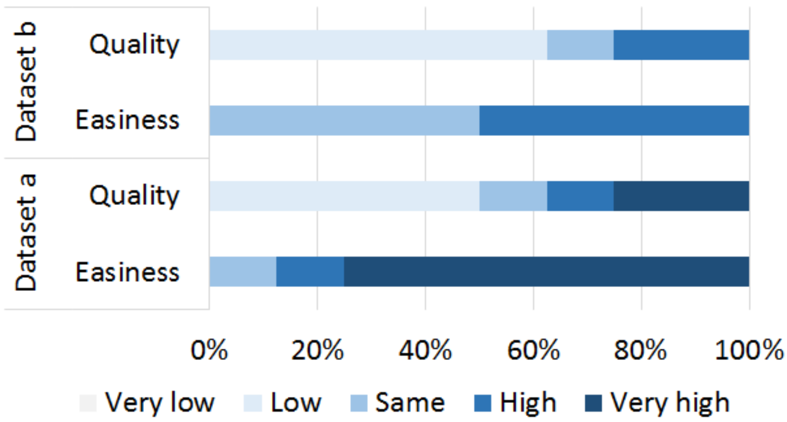


Figure 6.6 The bars represent the percentage of user selections for quality and easiness grouped by dataset. The answers range from very low (light blue) to very high (dark blue).

The Fig. 6.6 shows the percentage of selections in each level for quality and ease of use (usability) for both datasets. Concerning usability, the two studies had no negative selections. The general average was 4.0625 points (max = 5, min = 2, stdev = 1.44). This assessment reflects the simplicity of our interface to focus on a region (zoom + head rotations) and to set parameters of interest (window).

Some firs time users had trouble interact in the beginning, but in general learned fast and had no problems to handle the fracture identification task. Other users demonstrated interest in a more natural interface where they could use their hands to manipulate the 3D volume. While the search for naturality is the straightforward way to go, we focused on the standardization of the interface to increase affordance between the mobile and desktop platforms. This also allows faster integration with existing imaging systems, which favors dissemination. In the future, with the increasing popularity of VR devices and 3D controls, more tools can be added to aid in the analysis, e.g. the use of cutting planes. Those will require other user actions and may benefit from natural gestures.

Concerning the quality of the reconstructed image volume, we rely on the subjective analysis of radiologists and medical physicists, who are very demanding in terms of image attributes. In both studies their answers present a general average of 2.85 (max = 5, min = 2, stdev = 1.1474). The visualization of dataset a (avg = 3.125) has been perceived as of better quality than the dataset b (avg = 2.65), even with a smaller number of slices. This probably occurred due to the bone filter used in image acquisition, highlighting the surface structures and consequently generating a sharper image.

Notice that the image quality is impaired by low resolution of the Oculus Rift DK2. Besides, the algorithms have been optimized to run on mobile devices while most 3D images currently available to radiologists are processed on dedicated workstations. Even with these limitations, they were able to diagnose the surface fractures of the volume, as previously shown.

6.2.3 Exploratory Analysis

Another contribution of our research is the user's opinion of where VR applications can be useful in medicine. According to 75% of radiologists, a VR interface such as ours has benefits in virtual endoscopies, like colonoscopy, where the conventional procedure is the use of mouse and keyboard to navigate in a 3D volume displayed on a 2D monitor.

The 68.8% of the participants think this interface would be useful for communication with referring physicians. The doctors explained that medical assistants have difficulty to understand the 2D slices. They are unable to make an appropriate mental spatial reconstruction. A recent work Rosenkratz et (2016) has shown that promoting communication between the radiologist and the referring physician improved the understanding of the images and the exams report, consequently affecting the patient healthcare. Our results highlight the potential of VR to analyze 3D images with intuitive visual representations that instigate discussion among the medical staff. This is particularly important in planning surgery and analyzing complex fractures, as highlighted by 75% of subjects.

Additionally, 10 out of 16 participants stated that they see benefits in using a VR interface in consultation with patients to explain procedures and exams. According to 56.3% of the users, our interface would be useful for exams documentation and reconstruction, which are typical tasks of the medical physicists. Furthermore, the medical physicist suggested the possibility of making cuts to remove volume structures, and then save the results. This can be explored in future works on 3D user interfaces for image-based diagnosis.

We then explored further, asking the participants what tools they would like to see integrated into the interface to help them in diagnosis. Most of them (62.5%) indicated that oblique cuts in the volume (in arbitrary planes) would be useful. This is reported to be crucial to visualize internal structures. The use of transparency in the mapping of windowing parameters to the volume rendering helps seeing internal structures. However, it is known that humans do not deal well with several transparent layers (KAWABE; MARUYA; NISHIDA, 2015). Besides, to explore the wider visualization space that VR provides, 10 physicians (62.5%) would like to be able to navigate in 2D planes with reference lines/planes displayed in the volume. They are used to this type of navigation in conventional diagnostic workstations. In another analogy to the current radiologist workstation, 62.5% of the subjects would like to apply annotations and use measurement tools in the VR interface. Finally, 37.5% of the subjects mentioned the need of voice commands for report writing.

6.2.4 Discomforts

Eventual discomforts with the interface were measured with an adapted Simulator Sickness Questionnaire (KENNEDY et al., 1993). All participants performed the task standing upright and without prescription glasses. Figure 6.7 shows the distribution of the discomforts reported by the subjects. Overall, a very low level of discomfort was reported. Blurred vision was the main issue, affecting near 25% of the users. Similarly, eye strain has been reported by 3 participants (2 moderate and 1 severe). These are linked to 5 users that reported some degree of myopia. In a day-by-day workflow with a VR interface, they should be allowed to wear their prescription glasses or adjust the HMD optics individually.

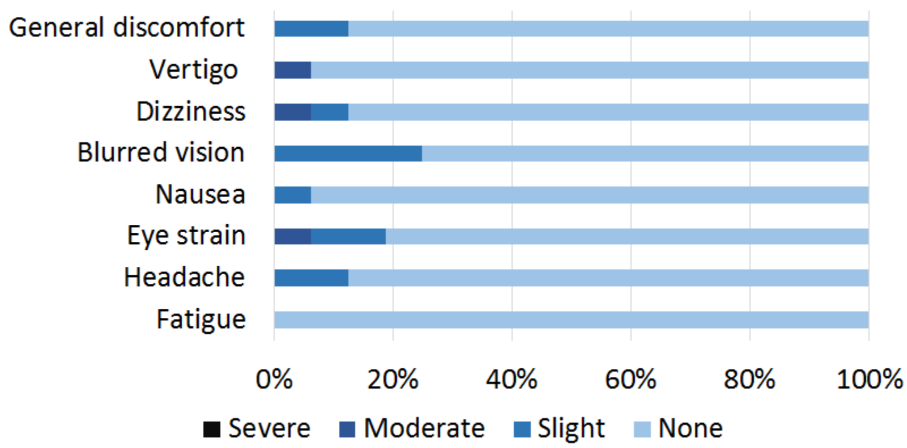


Figure 6.7 Results of the Simulator Sickness Questionnaire. Each bar shows the intensity of each evaluated discomfort during the execution of the fracture identification tasks. The overall discomfort is surprisingly low.

Furthermore, two subjects reported slight headaches which can be due to the visual strain but are also possibly related to the intensity of head movements around the volume. This justifies a future effort to design a more natural interaction. Less than 15% of users felt some general discomfort as well. These are associated with the first use of VR and current limitations of these devices.

6.2.5 General Comments

The general comments of the radiologists were analyzed using the Discursive Textual Analysis (DTA) qualitative technique (MORAES, 2003), constituted of three steps – unitarization, categorization, communication. The unitarization fragments the text in their elementary units or basic meanings. The categorization establishes the relationships between the elementary units, combining and classifying them into more complex categories. The communication is the production of a meta-text with new emerging comprehension.

Mainly two limitations were pointed out by the radiologists: low spatial resolution and contrast, and the difficulties for those with low visual acuity. However, they pointed out the potentiality to improve surgical planning and anatomy learning. Some comments suggest the implementation of existing medical computational tools, indicating toughness to overcome the established practice in the workstation environment and to embrace VR as a new paradigm in medical interpretation.

7 CONCLUSION

The research presented in this thesis investigated the medical imaging analysis based on mobile and VR interfaces. Through user experiments, we measured the performance of a mobile viewer, in terms of computational performance, as well as the accuracy of the diagnostic interpretation. We investigated also the capacity to identify fractures using a virtual reality interface, and the radiologists perception about its use on medical imaging.

Firstly, we showed a new approach that provides an optimization for fast medical image transfer and visualization suitable for mobile and stationary devices. Our approach was implemented and validated using a real use case, the application Animati Viewer, which is a web viewer for diagnostic images, part of the Animati PACS.

Contrarily to previous approaches, ours keeps the application within the memory constraints, minimizing data transferring whenever possible, allowing the application to run on a variety of devices (including tablets and smartphones). Moreover, it does that without sacrificing the user experience. Experimental data point that over 90% of the users did not notice any delays or degraded image quality, and when they did, this did not impact on the clinical decisions.

The combined activities and orchestration of our methods allow the image viewer to run on resource-constrained environments, such as those with low network bandwidth or little available memory. These results demonstrate the ability to explore the use of mobile devices as a support tool in the medical workflow, that was studied in the following experiment.

In the second experiment, we propose a multivariable user study that investigates the diagnostic concordance between image analysis based on mobile interfaces and conventional workstations. We performed a between-subjects task-analysis using CT, MRI and radiography datasets. Moreover, we investigated the adequacy of the screen size, image quality, usability and the availability of the tools necessary for the analysis. Radiologists, members of several teams, participated in the experiment under real work conditions. They read the studies both on mobile and desktop devices, in such a way that the mobile analysis was an additional step that did not replace the workstation analysis. A total of 64 studies with 93 main diagnoses were analyzed.

Our results showed that, in most cases, the radiologists can perform a mobile diagnosis and achieve the same results of those produced in full-featured desktop workstations. Under the circumstances of our experiment, screen size and image quality had no effect in the mobile diagnosis process. In addition, the mobile viewer used in the experiment presented a favorable evaluation of usability as demonstrated by the results of issued questionnaires.

Results showed that 56 cases were classified with complete concordance (87.69%), 5 cases with almost complete concordance (7.69%) and 1 case (1.56%) with partial concordance. Only 2 studies presented discordance between the reports (3.07%). Out of 64 studies (93 diagnoses), only 3 presented a significant level of disagreement between the results of a mobile and a desktop.

The main reason to explain the cause of those disagreements was the lack of multiplanar reconstruction tool in the mobile viewer. As pointed out by the participants, a multiplanar reconstruction tool was missing, which is required for some types of diagnosis, especially if performed by less experienced radiologists.

In the light of our results, we concluded that for emergency image modalities, a mobile system as the one used in our experiment provides benefits to patients' healthcare, allowing accurate and swift study interpretation. The advantages are also extended to the radiologists, who can access features of PACS outside their usual desktop workplace. Accessing medical information through mobile devices from anywhere can be further explored for collaborative diagnosis, which could result in more effective reports. Moreover, this technology can be used by other physicians in patient appointments and for online exams distribution, reducing the costs and environmental impacts caused by printing process. In addition, the favorable results about 3D images in diagnosis, motivated us to the perform a third experiment.

So, in the last part of this thesis, we presented a user study with medical specialists to assess diagnostic effectiveness of VR usage in fracture identification.

We developed an engine for efficient parallel processing based on medical images and suitable for mobile and desktop devices. We also implemented a lossless server algorithm that preprocesses the exam data and sends them to the remote application. Our approach has been designed to integrate the VR diagnosis tool with conventional PACS systems in order to provide a new interface for medical staff integrated with their current tools.

Then, we performed a user study with medical specialists to assess diagnostic effectiveness of VR usage in fracture identification. We performed experiments to validate the proposed approaches with sixteen expert professionals in image diagnostic procedures. Subjects were challenged to identify fractures in head CT exams in a virtual environment. We then compared their interpretation with a list of fractures preliminarily diagnosed in a conventional way by a dissociate pool of experts. In addition, we assessed the subjects perception of the 3D reconstruction quality, ease of interaction and ergonomy (comforts/discomforts). In this experiment, we also inquired the subjects about cases in which VR can provide potential benefits for the medical workflow and consequently for the patients' healthcare.

The results have shown high effectiveness in identifying superficial fractures for two different volume exams. However, we found that viewing only the volume surface is not enough for the complete diagnosis, as deeply located internal structures are hard to visualize on the reconstructed volume. These results support our premise of VR being suitable to provide a more intuitive interface for the whole chain of the medical care. One remarkable observation is that it may encourage communication between referring physicians and radiologists as it increases the exam comprehension by the non-specialist. Increased communication is often correlated with better decision-making (ROSENKRANTZ et al., 2016).

7.1 Future Work

As shown in the related works, the mobile diagnosis is a more established research issue than medical images with virtual reality. Nevertheless, related to our experiments, we suggest the investigation of the impact of adding to the mobile application the set of missing tools identified by the participants. MPR, for instance, is available in some mobile image viewing applications, such as Osirix. However, it is unknown how the processing time required to build multiplanar data impacts on the usability and the diagnosis result. We believe it would reduce the lack of features that differentiates the mobile and desktop environment, which was the main cause of disagreement we encountered.

Collaborative diagnosis is another important research problem on mobile health. Physicians often need to discuss opinions with colleagues for a more accurate diagnosis, however most often use tools not appropriate for this, such as email or social networks. By means of tools that motivate the sharing of information in a safe way, we can ensure the ethical rights of patient data and improving the quality of the medical discussion.

Regarding our VR experiment, a hypothesis to be verified in a future work could be if referring physicians have a more complete and intuitive interface to analyze the results of imaging exams using 3D viewing, and if is possible to increase their understanding and correlation between the imaging findings and clinical examination.

The application of VR in the healthcare is a growing research area and is necessary to establish in which cases this technology has real benefits. In psychology, for example, immersive simulators are currently used for the treatment of phobias, such as fear of height or flying by plane. VR can be also explored to distract patients during long or painful medical procedures, as an example blood collection in children. Other applications currently in development are surgery planning, learning and training of new physicians. In radiology image analysis, the potentially infinite viewing and working space provided by VR can be revolutionizing to the way physicians interact with patient data, creating a new paradigm in medical imaging interpretation.

REFERENCES

BANGOR, A.; KORTUM, P.; MILLER, J. Determining what individual SUS scores mean: adding an adjective rating scale. **Journal of usability studies**, [S.l.: s.n.], v.4, n.3, 2009, p.114–123.

BEURDEN, M. H. van; IJSSELSTEIJN, W.; JUOLA, J. Effectiveness of stereoscopic displays in medicine: a review. **3D Research**, [S.l.: s.n.], v.3, n.1, 2012, p.1–13.

BHATIA, A. et al. Intra and inter-observer reliability of mobile tablet pacs viewer system vs standard pacs viewing station-diagnosis of acute central nervous system events. **Open Journal of Radiology**, [S.l.: s.n.], 2013.

BRIDGE, P. et al. The development and evaluation of a medical imaging training immersive environment. **Journal of medical radiation sciences**, [S.l.: s.n.], v.61, n.3, 2014, p.159–165.

BROOKE, J. SUS: a retrospective. **Journal of usability studies**, [S.l.: s.n.], v.8, n.2, 2013, p.29–40.

BROOKE, J. et al. SUS-A quick and dirty usability scale. **Usability evaluation in industry**, [S.l.: s.n.], v.189, n.194, 1996, p.4–7.

CHOUDHRI, A. F. et al. Handheld device review of abdominal CT for the evaluation of acute appendicitis. **Journal of digital imaging**, [S.l.: s.n.], v.25, n.4, 2012, p.492–496.

CHOUDHRI, A. F.; RADVANY, M. G. Initial experience with a handheld device digital imaging and communications in medicine viewer: osirix mobile on the iphone. **Journal of digital imaging**, [S.l.: s.n.], v.24, n.2, 2011, p.184–189.

CORREA, B. et al. Medical image analysis using mobile devices. In: ACM SYMPOSIUM ON APPLIED COMPUTING, 2008. **Proceedings...** [S.l.: s.n.], 2008. p.1380–1384.

DE MAIO, P. et al. Diagnostic accuracy of an iPhone DICOM viewer for the interpretation of magnetic resonance imaging of the knee. **Clinical Journal of Sport Medicine**, [S.l.: s.n.], v.24, n.4, 2014, p.308–314.

ESCOBAR, M. M. et al. Evaluation of monoscopic and stereoscopic displays for visual–spatial tasks in medical contexts. **Computers in biology and medicine**, [S.l.: s.n.], v.61, 2015, p.138–143.

FAGGIONI, L. et al. iPad-based primary 2D reading of CT angiography examinations of patients with suspected acute gastrointestinal bleeding: preliminary experience. **The British journal of radiology**, [S.l.: s.n.], v.88, n.1047, 2015, p.20140477.

FOO, J.-L.; LOBE, T.; WINER, E. A virtual reality environment for patient data visualization and endoscopic surgical planning. **Journal of Laparoendoscopic & Advanced Surgical Techniques**, [S.l.: s.n.], v.19, n.S1, 2009, p.s211–s217.

FRIEDMAN, T. et al. 3D printing from diagnostic images: a radiologist's primer with an emphasis on musculoskeletal imaging—putting the 3d printing of pathology into the hands of every physician. **Skeletal radiology**, [S.l.: s.n.], v.45, n.3, 2016, p.307–321.

GALLO, L.; PLACITELLI, A. P.; CIAMPI, M. Controller-free exploration of medical image data: experiencing the kinect. In: COMPUTER-BASED MEDICAL SYSTEMS (CBMS), 2011 24TH INTERNATIONAL SYMPOSIUM ON. **Proceedings. . .** [S.l.: s.n.], 2011. p.1–6.

GLAZER, G. M.; RUIZ-WIBBELSMANN, J. A. The Invisible Radiologist 1. **Radiology**, [S.l.: s.n.], v.258, n.1, 2011, p.18–22.

HÄNEL, C. et al. Interactive 3D visualization of structural changes in the brain of a person with corticobasal syndrome. **Frontiers in neuroinformatics**, [S.l.: s.n.], v.8, 2014.

JACKSON, V. P. et al. RADPEER™ scoring white paper. **Journal of the American College of Radiology**, [S.l.: s.n.], v.6, n.1, 2009, p.21–25.

JOHN, S. et al. The iPad tablet computer for mobile on-call radiology diagnosis? Auditing discrepancy in CT and MRI reporting. **Journal of digital imaging**, [S.l.: s.n.], v.25, n.5, 2012, p.628–634.

KASERER, M. **DICOM Web Viewer**. 2013. Tese (Doutorado em Ciência da Computação) — Technische Universität Wien.

KAWABE, T.; MARUYA, K.; NISHIDA, S. Perceptual transparency from image deformation. **Proceedings of the National Academy of Sciences**, [S.l.: s.n.], v.112, n.33, 2015, p.E4620–E4627.

KENNEDY, R. S. et al. Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. **The international journal of aviation psychology**, [S.l.: s.n.], v.3, n.3, 1993, p.203–220.

KIM, C. et al. A feasibility study of real-time remote CT reading for suspected acute appendicitis using an iPhone. **Journal of digital imaging**, [S.l.: s.n.], v.28, n.4, 2015, p.399–406.

KIM, D. K. et al. A mobile tele-radiology imaging system with JPEG2000 for an emergency care. **Journal of digital imaging**, [S.l.: s.n.], v.24, n.4, 2011, p.709–718.

KIM, M. S. et al. Exploring the Usability of Mobile Apps Supporting Radiologists' Training in Diagnostic Decision Making. **Journal of the American College of Radiology**, [S.l.: s.n.], v.13, n.3, 2016, p.335–343.

KING, F. et al. An immersive virtual reality environment for diagnostic imaging. **Journal of Medical Robotics Research**, [S.l.: s.n.], v.1, n.01, 2016, p.1640003.

LICURSE, M. Y. et al. Comparison of diagnostic accuracy of plain film radiographs between original film and smartphone capture: a pilot study. **Journal of digital imaging**, [S.l.: s.n.], v.28, n.6, 2015, p.646–653.

LIN, Q. et al. Immersive virtual reality for visualization of abdominal CT. In: SPIE MEDICAL IMAGING. **Proceedings...** [S.l.: s.n.], 2013. p.867317–867317.

MC LAUGHLIN, P. et al. Emergency CT brain: preliminary interpretation with a tablet device: image quality and diagnostic performance of the apple ipad. **Emergency radiology**, [S.l.: s.n.], v.19, n.2, 2012, p.127–133.

MELVIN, C. et al. Managing errors in radiology: a working model. **Clinical radiology**, [S.l.: s.n.], v.59, n.9, 2004, p.841–845.

MIRHOSSEINI, K. et al. Benefits of 3D immersion for virtual colonoscopy. In: DVIS (3DVIS), 2014 IEEE VIS INTERNATIONAL WORKSHOP ON, 3. **Proceedings...** [S.l.: s.n.], 2014. p.75–79.

MORAES, R. A storm of light: comprehension made possible by discursive textual analysis. **Ciência & Educação**, [S.l.: s.n.], v.9, n.2, 2003, p.191–211.

NI, T.; BOWMAN, D. A.; CHEN, J. Increased display size and resolution improve task performance in information-rich virtual environments. In: GRAPHICS INTERFACE 2006. **Proceedings...** [S.l.: s.n.], 2006. p.139–146.

NORWECK, J. T. et al. ACR–AAPM–SIIM Technical Standard for Electronic Practice of Medical Imaging. **Journal of digital imaging**, [S.l.: s.n.], 2013, p.1–15.

O'CONNELL, T. W.; PATLAS, M. N. Mobile devices and their prospective future role in emergency radiology. **The British journal of radiology**, [S.l.: s.n.], v.89, n.1061, 2016, p.20150820.

PARK, J. B. et al. An assessment of the iPad 2 as a CT teleradiology tool using brain CT with subtle intracranial hemorrhage under conventional illumination. **Journal of digital imaging**, [S.l.: s.n.], v.26, n.4, 2013, p.683–690.

PARK, J. H. et al. Diagnostic performance of smartphone reading of the coronary CT angiography in patients with acute chest pain at ED. **The American Journal of Emergency Medicine**, [S.l.: s.n.], v.34, n.9, 2016, p.1794–1798.

PASHA, M. F. et al. An android-based mobile medical image viewer and collaborative annotation: development issues and challenges. **JDCTA**, [S.l.: s.n.], v.6, n.1, 2012, p.208–217.

PIANYKH, O. S. **Digital imaging and communications in medicine (DICOM)**: a practical introduction and survival guide. [S.l.]: Springer Science & Business Media, 2008.

RANDALL, D. et al. The Oculus Rift virtual colonoscopy: introducing a new technology and initial impressions. **Journal of Biomedical Graphics and Computing**, [S.l.: s.n.], v.6, n.1, 2015, p.p34.

RENGIER, F. et al. 3D printing based on imaging data: review of medical applications. **International journal of computer assisted radiology and surgery**, [S.l.: s.n.], v.5, n.4, 2010, p.335–341.

RHEA, J. T.; NOVELLINE, R. A. How to simplify the CT diagnosis of Le Fort fractures. **American Journal of Roentgenology**, [S.l.: s.n.], v.184, n.5, 2005, p.1700–1705.

RICCIARDI, F. et al. Scalable Medical Viewer for Virtual Reality Environments. In: **Augmented and Virtual Reality**. [S.l.]: Springer, 2015. p.233–243.

RODRIGUES, M. et al. Radiology smartphone applications; current provision and cautions. **Insights into imaging**, [S.l.: s.n.], v.4, n.5, 2013, p.555–562.

ROSENKRANTZ, A. B. et al. Technology-Assisted Virtual Consultation for Medical Imaging. **Journal of the American College of Radiology**, [S.l.: s.n.], 2016.

SCHLECHTWEG, P. M. et al. Mobile Image Interpretation: diagnostic performance of ct exams displayed on a tablet computer in detecting abdominopelvic hemorrhage. **Journal of digital imaging**, [S.l.: s.n.], v.29, n.2, 2016, p.183–188.

SCHUBERT, C.; LANGEVELD, M. C. van; DONOSO, L. A. Innovations in 3D printing: a 3d overview from optics to organs. **British Journal of Ophthalmology**, [S.l.: s.n.], 2013, p.bjophthalmol–2013.

SEONG, N. J. et al. Off-site smartphone reading of CT images for patients with inconclusive diagnoses of appendicitis from on-call radiologists. **American Journal of Roentgenology**, [S.l.: s.n.], v.203, n.1, 2014, p.3–9.

SZÉKELY, A.; TALANOW, R.; BÁGYI, P. Smartphones, tablets and mobile applications for radiology. **European journal of radiology**, [S.l.: s.n.], v.82, n.5, 2013, p.829–836.

TYNDIUK, F. et al. Impact of large displays on virtual reality task performance. In: COMPUTER GRAPHICS, VIRTUAL REALITY, VISUALISATION AND INTERACTION IN AFRICA, 3. **Proceedings...** [S.l.: s.n.], 2004. p.61–65.

VENSON, J. E. et al. Dynamic Optimization for Fast Image Transfer and Visualization for Mobile and Stationary Devices: a performance evaluation using animati viewer. **Workshop de Informática Médica**, [S.l.: s.n.], 2015.

VENSON, J. E. et al. Medical imaging VR: can immersive 3d aid in diagnosis? In: ACM CONFERENCE ON VIRTUAL REALITY SOFTWARE AND TECHNOLOGY, 22. **Proceedings...** [S.l.: s.n.], 2016. p.349–350.

VENSON, J. E. et al. Efficient medical image access in diagnostic environments with limited resources. **Research on Biomedical Engineering**, [S.l.: s.n.], n.AHEAD, 2017, p.0–0.

VENSON, J. E. et al. A Case-based Study with Radiologists Performing Diagnosis Tasks in Virtual Reality. In: TO APPEAR- MEDINFO. **Proceedings...** [S.l.: s.n.], 2017.

WANG, Z. et al. How effective is mobile browser cache? In: ACM WORKSHOP ON WIRELESS OF THE STUDENTS, BY THE STUDENTS, FOR THE STUDENTS, 3. **Proceedings...** [S.l.: s.n.], 2011. p.17–20.

WEST, D. How mobile devices are transforming healthcare. **Issues in technology innovation**, [S.l.: s.n.], v.18, n.1, 2012, p.1–11.

ZWART, C. M. et al. Selection and Pilot Implementation of a Mobile Image Viewer: a case study. **JMIR mHealth and uHealth**, [S.l.: s.n.], v.3, n.2, 2015.

APPENDIX A SUBMISSIONS

- VENSON, J. E. et al. Dynamic Optimization for Fast Image Transfer and Visualization for Mobile and Stationary Devices: a Performance Evaluation Using Animati Viewer. Workshop de Informática Médica. 2015. [**ACCEPTED**]
- VENSON, J. E. et al. Efficient medical image access in diagnostic environments with limited resources. Research on Biomedical Engineering, 2017. [**ACCEPTED**]
- VENSON, J. E. et al. Immersive Visualization for 3D Volumetric Medical Images. Symposium on Virtual and Augmented Reality. 2016. [**ACCEPTED**]
- VENSON, J. E. et al. Medical imaging VR: can immersive 3d aid in diagnosis?. In:ACM Conference on Virtual Reality Software and Technology,22.Proceedings. 2016. p.349–350. [**ACCEPTED**]
- VENSON, J. E. et al. A Case-based Study with Radiologists Performing Diagnosis Tasks in Virtual Reality. MedInfo. 2017. [**ACCEPTED**]
- VENSON, J. E. et al. Diagnostic concordance between mobile interfaces and conventional workstations for emergency imaging assessment. International Journal of Medical Informatics. 2017. [IN REVIEW]
- Post published in the november (2016) edition of Jornal da Imagem, maintained by the Radiological and Diagnostic Imaging Society of Sao Paulo (SPR), available online and in print.
  https://issuu.com/sociedadepaulistaderadiologia/docs/ji_459_-_nov_16/4.

APPENDIX B PARTICIPANT INFORMED CONSENT FORM USED FOR EXPERIMENT I AND II

B.1 In portuguese

Esse termo é um documento para que você saiba como será o experimento e escolha livremente se quer ou não participar. Após ler as informações, caso aceite participar, assine ao final deste documento, que está em duas vias. Caso não queira participar, você não será penalizado de forma alguma.

Objetivo: Com este trabalho pretende-se mensurar a capacidade do uso de aplicativos móveis para diagnóstico de imagens, bem como comunicação entre a equipe médica para a interpretação colaborativa e otimização aos cuidados da saúde do paciente. Para isso, será avaliada a concordância dos achados clínicos obtidos usando um tablet, em comparação aos achados obtidos através do fluxo tradicional (computadores desktop).

Benefícios: benefícios são o desenvolvimento e aprimoramento de ferramentas de computação para o auxílio do processo de diagnóstico.

Riscos: existe risco de desconforto ao responder questionários e risco de perda da confidencialidade dos dados.

Etapas do teste: A duração do experimento varia de acordo como tipo de exame analisado e possui no mínimo três etapas:

1. Pré-questionário de caracterização.
2. Uso da aplicação móvel: etapa na qual você usará um iPad para analisar determinado exame.
3. Conferência do exame: etapa na qual você usará sua estação de trabalho convencional para revisar o laudo obtido no dispositivo móvel.
4. Pós-questionário parcial referente ao teste realizado.
5. Pós-questionário final referente a aspectos gerais do teste e uso de tecnologia no contexto médico.

Obs.: O pesquisador acompanhará todo o procedimento.

Equipamentos utilizados durante o teste:

1. iPad.
2. Sua estação de trabalho convencional (Workstation).

Direitos do participante:

1. Todas as informações obtidas neste estudo a seu respeito serão anonimizadas e utilizadas apenas para fins estatísticos.
2. Todas as informações obtidas neste estudo a respeito dos dados dos pacientes serão anonimizadas e utilizadas apenas para fins estatísticos.
3. Você tem toda a liberdade de abandonar estudo a qualquer momento sem penalização.

Obs: Em nenhum momento sua capacidade enquanto profissional será avaliada.

Concordo voluntariamente em participar deste estudo:

______________________________	________________________
Participante	Data
______________________________	________________________
Pesquisador	Data

Contato do pesquisador: José Eduardo Venson (046999087357 | jevenson@inf.ufrgs.br)

APPENDIX C PATIENT INFORMED CONSENT FORM

C.1 In portuguese

Este termo esclarece como os dados do seu exame poderão ser usados em um experimento científico caso autorize o seu uso. Escolha livremente se deseja ou não contribuir com a pesquisa. Caso não queira participar, você não será penalizado de forma alguma.

Autorizo a veiculação das imagens do meu exame para fins científicos. Estou ciente, também, que tais procedimentos serão realizados sem qualquer ônus financeiro, presente ou futuro. Todas as informações obtidas neste estudo a respeito dos dados dos pacientes serão anonimizadas e utilizadas apenas para fins estatísticos.

Objetivo: A pesquisa que usará as imagens, pretende avaliar a capacidade do uso de aplicativos móveis para diagnóstico, a fim de melhorar os procedimentos aplicados aos cuidados da saúde do paciente.

Riscos: existe risco de perda da confidencialidade dos dados.

Benefícios: benefícios são o desenvolvimento e aprimoramento de ferramentas de computação para o auxílio do processo de diagnóstico.

Concordo voluntariamente em participar deste estudo:

Paciente ______________________ Data ______________________

APPENDIX D CHARACTERIZATION QUESTIONNAIRE - EXPERIMENT I AND II

1. Gender: (Female, Male, other)
2. Profession: (Senior Radiologist, Radiologist, Resident Radiologist, Medical Physicist, other)
3. What is your specialty in radiology?
4. What is your age range?
5. Rate your experience using mobile apps: from 1 (use less than once a month) to 5 (use several times a day)

APPENDIX E CHARACTERIZATION QUESTIONNAIRE - EXPERIMENT III

1. Gender: (Female, Male, other)
2. Profession: (Senior Radiologist, Radiologist, Resident Radiologist, Medical Physicist, other)
3. What is your specialty in radiology?
4. What is your age range?
5. Have you ever had any experience with virtual reality? (Yes) (No)

APPENDIX F SIMULATOR SICKNESS QUESTIONNAIRE - SUS

Indicate how much each symptom below is affecting you right now in the following scale: None, Slight, Moderate, Severe

1. General discomfort
2. *Vertigo
3. Dizziness
4. Blurred vision
5. Nausea
6. Eye strain
7. Headache
8. Fatigue

* Vertigo is experienced as loss of orientation with respect to vertical upright.

APPENDIX G RESUMO EXTENDIDO EM PORTUGUÊS

G.1 Contexto

A radiologia é especialidade médica mais informatizada, graças a difusão de protocolos e a digitalização dos processos. Com os avanços da tecnologia, o diagnóstico por imagens se mantém em constante evolução e tais mudanças nunca tiveram tanta repercussão sobre o trabalho dor profissionais de saúde como agora. Nosso desafio enquanto pesquisadores de computação é propor abordagens que facilitem o trabalho médico, instigue a colaboração e, por fim, como objetivo mais audacioso, melhore os cuidados à saúde das pessoas.

Clínicas e hospitais, visando melhorar a qualidade dos serviços e o atendimento aos pacientes, estão integrando seus sistemas de informação, para que sigam os conceitos adotados mundialmente, como o sistema de comunicação e arquivamento de imagens (PACS). Com essa integração, possibilita-se a criação de sistemas de gerenciamento de imagens e redes de larga escala, permitindo que as informações dos pacientes e as imagens sejam compartilhadas e visualizadas local e remotamente.

No entanto, nos processos de diagnóstico baseados em imagens, os radiologistas interagem com uma estação de trabalho dedicada com monitores de vídeo especialmente concebidos e calibrados para interpretar os exames de imagem. Além dos altos requisitos de hardware, essas estações de trabalho devem estar equipadas com um sistema PACS que freqüentemente dependem da instalação de plug-ins. Tais ambientes foram desenvolvidos para usuários treinados em imagens médicas digitais, como radiologistas e físicos médicos. Em vista disso, torna-se difícil para outros especialistas, como médicos solicitates (por exemplo, cardiologistas, neurologistas e cirurgiões) acessarem e entender os exames por meios digitais.

G.2 Métodos

Nesse contexto, esta dissertação investiga a inserção de interfaces alternativas para análise de imagens médicas diagnósticas. Ela está organizada em duas áreas principais, a primeira diz respeito ao diagnóstico móvel, desde o desenvolvimento de ferramentas que permitam o acesso a imagens digitais em ambientes com recursos limitados, até a avaliação do diagnóstico realizado nesses ambientes comparado a dispositivos tradicionais (workstations radiológicas). A segunda etapa está relacionada a visualização avançada de exames volumétricos, nesse caso investigamos a capacidade diagnóstica de visualizar em realidade virtual, bem como a qualidade das reconstruções nesse ambiente, usabilidade e desconfortos dos usuários. Toda a experimentação e desenvolvimento foi realizada sobre sistemas profissionais e validados por médicos especialistas em imagens diagnósticas.

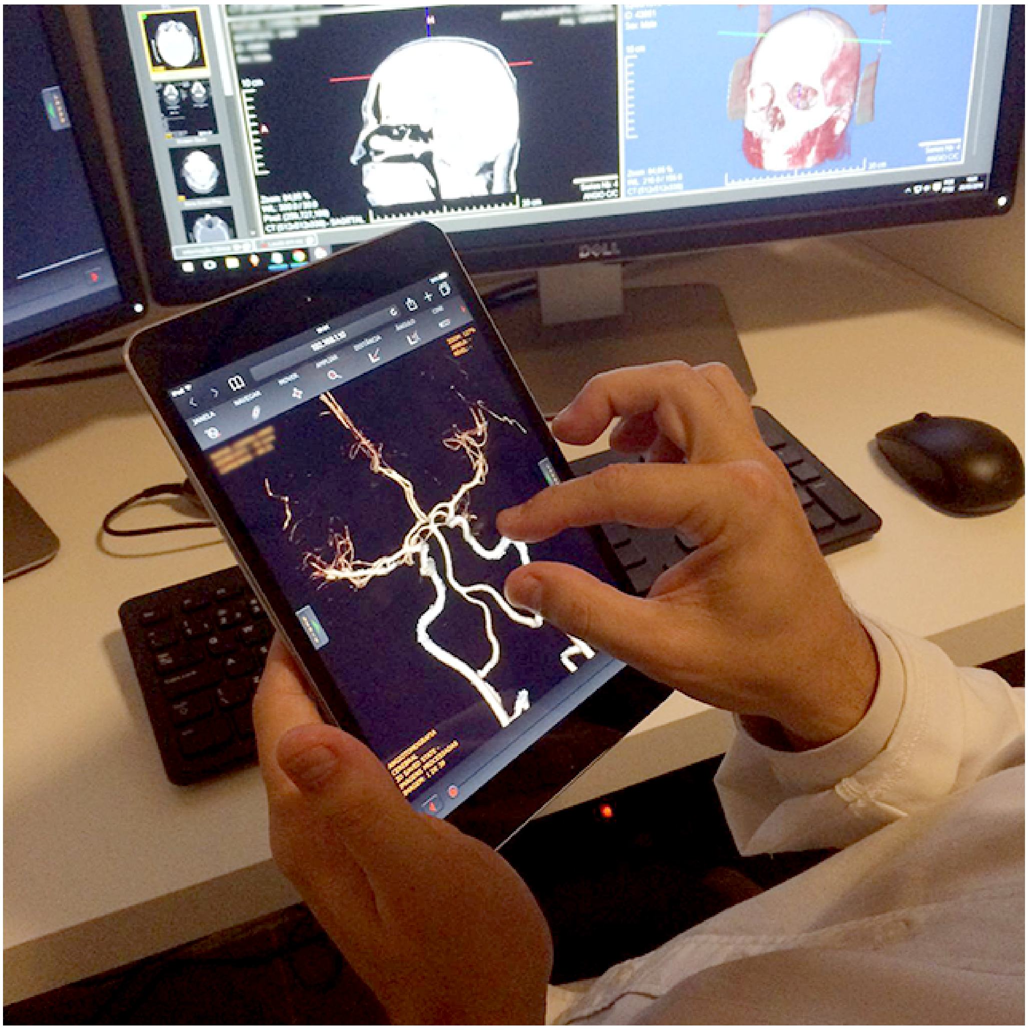


Figure G.1 Usuário manipulando a aplicação móvel durante um dos experimentos. Na frente está o Animati Viewer, visualizar móvel utilizado e validado nos experimentos I e II. Ao fundo uma workstation radiológica convencional.

G.3 Resultados

As principais contribuições referentes a aplicações móveis são técnicas para acesso eficiente a imagens médicas em ambientes com recursos limitados, como tablets e smartphones, um estudo do comportamento típico de médicos radiologistas ao utilizarem um visualizador móvel e as respectivas avaliações de usabilidade dessa aplicação.

Nossa abordagem mantém a aplicação dentro das limites de memória disponível, minimizando a transferência de dados sempre que possível e permitindo que a aplicação execute em uma variedade de dispositivos (incluindo tablets e smartphones). Destaca-se a preocupação com a experiência dos usuários, sendo que mais de 90% dos radiologistas não perceberam quaisquer atraso na transferência ou qualidade de imagem degradada.

Para o diagnóstico móvel, destaca-se a alta taxa de acerto para avaliação de exames de tomografia computadorizada (TC), ressonância magnética (RM) e radiografias, quando comparado a computadores desktop. Um total de 64 estudos com 93 diagnósticos principais foram analisados. Sob as circunstâncias de nosso experimento, o tamanho da tela e qualidade de imagem não tiveram nenhum efeito no processo de diagnóstico móvel. Além

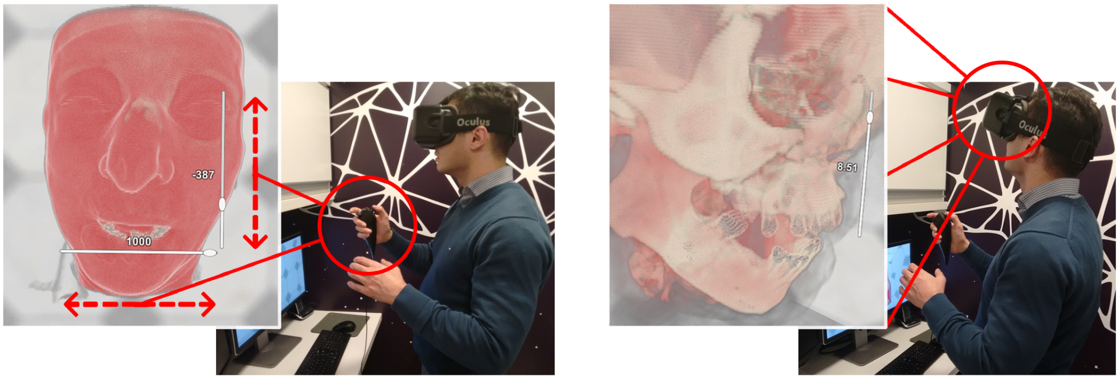


Figure G.2 Usuário interagindo com um conjunto de dados 3D através de nossa interface de realidade virtual utilizada no experimento III. À esquerda, altera-se o contraste para tecidos moles usando um joystick analógico. À direita, destaca-se as estruturas ósseas e através de rotações de cabeça uma determinada região é focada. Um vídeo suplementar (disponível em https://youtu.be/5TlwMYVJqPI) demonstra em detalhes o funcionamento da nossa interface.

disso, a aplicação móvel utilizada apresentou uma avaliação favorável de usabilidade.

Os resultados mostraram que 56 casos foram classificados com concordância completa ($87,69\%$), 5 casos com concordância quase completa ($7,69\%$) e 1 caso ($1,56\%$) com concordância parcial. Apenas 2 estudos apresentados discordância entre os relatórios (3.07%). De 64 estudos (93 diagnósticos), apenas 3 apresentaram um nível significativo de discordância.

Além disso, resultados obtidos na visualização de imagens médicas em realidade virtual mostraram uma alta taxa de acerto na identificação de fraturas expostas (para imagens 3D de TC). Os resultados demonstraram eficácia na identificação de fracturas superficiais para dois exames volumétricos diferentes. No entanto, descobrimos que visualizar apenas a superfície do volume não é suficiente para o diagnóstico completo, pois estruturas internas profundas são difíceis de visualizar no volume reconstruído. Esses resultados suportam a nossa premissa de que a realidade virtual pode fornecer uma interface mais intuitiva para todos os profissionais envolvidos no processo de diagnóstico.

A percepção dos radiologistas após utilizar a aplicação imersiva trouxe indicativos de quais áreas da medicina a realidade virtual pode trazer reais benefícios, como no planejamento de cirurgias, visualização de fraturas complexas, distração de pacientes em procedimentos dolorosos, entre outros.

G.4 Conclusões

A pesquisa apresentada nesta dissertação investigou a análise de imagens médicas com base em interfaces móveis e de realidade virtual. Através de experimentos de usuários, nós medimos o desempenho de um visualizador móvel, em termos de desempenho computacional, bem como a precisão da interpretação diagnóstica. Além disso, investigamos a capacidade de identificar fraturas usando uma interface de realidade virtual, e a percepção radiologistas sobre o seu uso em imagens médicas digitais.

À luz dos resultados apresentados, verifica-se o potencial dos dispositivos móveis para avaliação de imagens diagnósticas, principalmente em casos de emergência, sendo fundamental para agilidade no cuidado à saúde de pacientes. A realidade virtual na radiologia tem o potencial de revolucionar as interfaces para manipulação de dados clínicos, criando uma novo paradigma de interpretação em imagens médicas diagnósticas.

Sobre os trabalhos futuros, o diagnóstico colaborativo é um importante campo de pesquisa para aplicações móvies. Os médicos muitas vezes precisam discutir opiniões com os colegas para um diagnóstico mais preciso, porém a maioria costuma usar ferramentas não apropriadas, tais como e-mail ou redes sociais. Por meio de ferramentas móveis é possível fazer o compartilhamento de informações de uma forma segura, garantindo os direitos éticos dos dados dos pacientes e melhorando a qualidade da discussão médica.