A Case-based Study with Radiologists Performing Diagnosis Tasks in Virtual Reality

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Abstract

In radiology diagnosis, medical images are most often visualized slice by slice. At the same time, the visualization based on 3D volumetric rendering of the data is considered useful and has increased its field of application. In this work, we present a case-based study with 16 medical specialists to assess the diagnostic effectiveness of a Virtual Reality interface in fracture identification over 3D volumetric reconstructions. We developed VR volume viewer compatible with both the Oculus Rift and handheld-based head mounted displays (HMDs). We then performed user experiments to validate the approach in a diagnosis environment. In addition, we assessed the subjects' perception of the 3D reconstruction quality, ease of interaction and ergonomics, and also the users opinion on how VR applications can be useful in healthcare. Among other results, we have found a high level of effectiveness of the VR interface in identifying superficial fractures on head CTs.

Keywords: *Diagnostic Imaging, Volume Visualization, Virtual Reality Interface*

Introduction

In healthcare, Virtual Reality (VR) has been applied mostly on 3D simulations for training or planning surgeries. Virtual simulators have been especially successful in training minimally invasive and robotic procedures [1]. 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 [2]. 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 [3]. 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 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.

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 the efficiency of the analysis [4]. This is crucial as the profusion of data to be analyzed by the radiologist grows fast as new acquisition modalities and diagnostic techniques evolve.

In a preliminary study with 10 radiologists, we investigated 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 search fractures. Other areas have also been mentioned, including planning surgeries (90%), educational presentations/classes (70%), operating room, patient appointments and discussion with colleagues (60%). One of the possible innovations in the workflow is the generation of a 3D printed model of the patient specific-anatomy and pathology [5]. However, it is still expensive and limited in terms of modeling soft tissues and model modification. VR is a more flexible and inexpensive alternative.

Given this context, we report, in this paper, 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. 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 in a related work [6], 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 has substantially reduced. So, 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.

Related Work

Ricciardi et al. [7] discussed a medical viewer for 3D environments that can be usable on either desktop, head-mounted display or 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. [8] 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 for the display on conventional monitors and immersive environments 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. [9] 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 game controller. 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. The Oculus Rift was explored in virtual colonoscopy (VC) procedure [10]. 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 emphasize the need of future deployments to provide maximum performance. Likewise, Mirhosseini et al. [11] 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.

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 cyber sickness. This study was approved by the Institutional Review Board of our institution (nbr. 1.782.728).

System Design

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

The visualization engine runs on either a PC with the Oculus Rift or on a smartphone adapted as an HMD using Google Cardboard or other off-the-shelf or 3D printed mobile HMDs. 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, allows navigating through the visualization options. Fig. 1 (right) shows users interacting with a joystick to control windowing and zoom. Viewpoint is controlled with natural head rotations to look for a target position in the 3D volume.

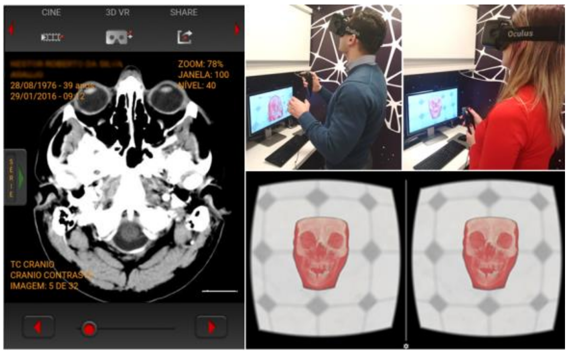

Figure 1: Integration of the VR interface with PACS. A 3D VR button is shown at the top of the left image. It triggers the 3D VR engine. On the right, we show the users interacting with a 3D dataset through our VR interface[1].

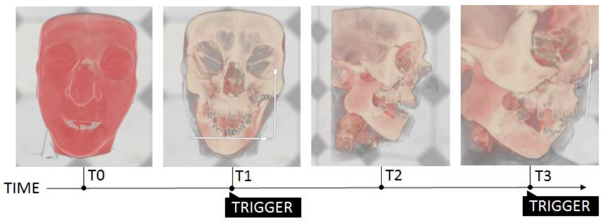

Figure 2: A typical timeline of user actions with the interface. T0 shows a centered initial position and windowing in tissue range. At T1, the windowing tool is activated through a click and the parameters are set to highlight bones. T2 shows the volume rotated due to a head movement. At T3, the zoom tool is activated to provide details on a specific region.

Fig. 2 shows an example sequence of actions applied with our interface. *T0* is the initial state in which the 3D volume is displayed in the center of the screen with standard windowing and viewpoint. At *T1* a joystick trigger is pushed to activate the windowing adjustment tool, displaying the two bars with window width and center values. They are changed moving the analog stick in four directions. The result of this change is observed in the second image, highlighting the density range of bone rather than soft tissue. The picture in *T2* represents the

[1] Please visit https://goo.gl/uSN47M to watch a short video demonstration of the interface.

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.

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 1 mm 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 data-set. Three neuroradiologists with 5 to 10 years of experience performed this analysis. 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.

Seven fractures have been identified in the dataset *a*, and six in dataset *b* by the committee of 3 experts. Doctors emphasized that some of these fractures are internal and small, hardly interpreted only viewing the 3D volume as they may be occluded by structures near the surface. After the studies interpretation, we prepared 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.

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 subspecialties. 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 an immersive 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 to avoid users to simulate slice-by-slice visualizations.

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 also 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 are 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*. 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) [12], using the questions most related to our case. 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.

Results and Discussion

We report results on the users' performance in identifying fractures, the subjective quality of the reconstructions and subjective comfort/discomfort.

Diagnostic effectiveness

Figs. 3 and 4 show the number of responses on each of the possible observations on 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. 4. Regarding the correct options, 7 radiologists (87.5%) correctly interpreted the lateral right orbit wall and right orbit floor. The right zygomatic arch has been found 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. 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. 3. 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 the only participant who is a medical physicist and is not expected to succeed in identifying fractures.

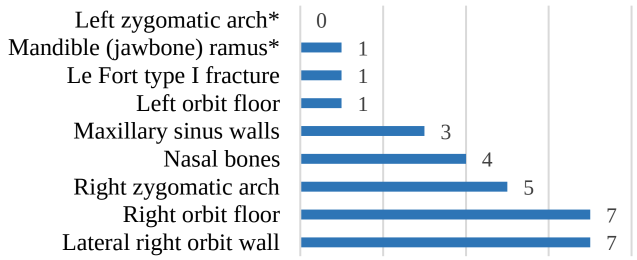

*Figure 3: Diagnostic effectiveness for dataset a. Possible fractures are in the y-axis. The x-axis shows the number of users that have marked each possible option. The * indicates that the respective bar represents a non-existent fracture.*

Fig. 4 shows the answers on the second exam (*b*) with six correct and two false choices. All radiologists found the depressed right anterior maxillary sinus wall (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 internal head structures, hardly seen without making cuts in the 3D volume or viewing on 2D slices. In the preliminary interpretation, the radiologists explicitly pointed to this possibility, and these results demonstrate that.

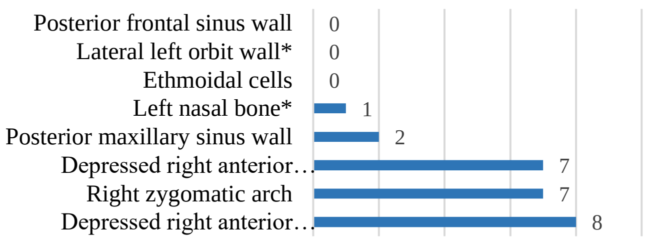

*Figure 4: Diagnostic effectiveness for dataset b. Possible fractures are in the y-axis. The x-axis shows the number of users that have marked each possible option. The * indicates that the respective bar represents a non-existent fracture.*

Similarly, to the first exam, the dataset *b* scored only one vote in one of the false alternatives (left nasal bone), and none in the other. The exam presents facial polytrauma affecting nearby structures. This seems to have induced 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 studies. Most radiologists, regardless of experience and specialty, found the outer skull fractures, for instance, in the zygomatic arch, anterior maxillary sinus wall and lateral orbit wall. Thus, we emphasize the high diagnostic effectiveness obtained with the VR interface, even though it was the first contact of the subjects with an immersive VR system. Results have also shown a limitation for identification of the internal fractures, which was expected as they are occluded by surface elements.

Usability and Quality

We also analyzed 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).

Fig. 5 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).

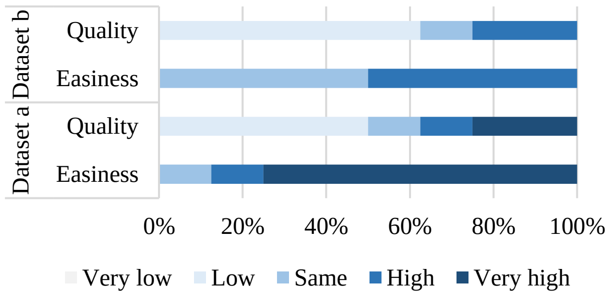

Figure 5: The bars represent the percentage of user selections for quality and easiness grouped by dataset. The answers range from very low (light blue) to very high (dark blue).

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 the relatively 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. Despite these limitations, they were able to diagnose the surface fractures of the volume, as previously shown.

Exploratory Analysis and Discomforts

Another contribution of our research is the user's opinion about 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 [6] 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.

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 [13]. Besides, 10 physicians (62.5%) would like to be able to navigate in 2D planes with reference lines/planes displayed in the volume. VR provides a 360º wide visualization space that enables volume and planar views to be placed side by side.

Finally, eventual discomforts with the interface were measured with an adapted Simulator Sickness Questionnaire. All participants performed the task standing upright and without prescription glasses. Fig. 6 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, 3 participants reported eyestrain (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.

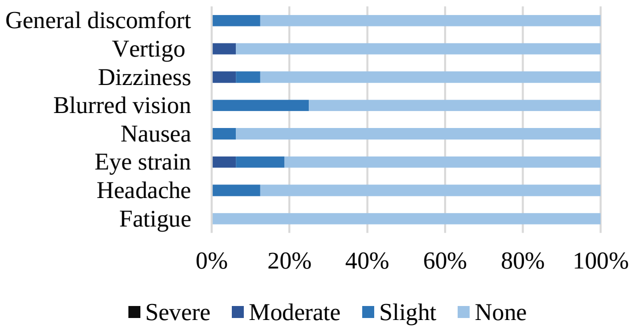

Figure 6: Each bar shows the intensity of each evaluated discomfort during the execution of the fracture identification tasks. The overall discomfort is surprisingly low.

Conclusion

In this paper, we presented 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.

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 [6].

Future work should focus on the assessment of long term use of VR goggles for image-based diagnosis.

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