Virtual Reality in Radiology: A Systematic Mapping Study

Renan Trévia
renan.trevia@edu.pucrs.br
Pontifical Catholic University of Rio Grande do Sul
Porto Alegre, Rio Grande do Sul, Brazil

Marcio Sarroglia Pinho
marcio.pinho@pucrs.br
Pontifical Catholic University of Rio Grande do Sul
Porto Alegre, Rio Grande do Sul, Brazil

ABSTRACT

In radiology, virtual reality has emerged as a candidate to solve some issues of the area, such as the ambient lighting and ergonomic postures when diagnosing.

The goal of this study is to explore the literature of virtual reality in radiology in order to define and describe the state-of-the-art in addition to finding gaps and opportunities for future research.

To do so, we carried out a systematic mapping study covering the period from January 2014 to July 2021. We initially found 329 papers to be reviewed, but after applying our exclusion criteria we ended up with 24 primary studies.

Our results suggest that the use of virtual reality has grown recently in the field, however there are many gaps and opportunities to explore in the area.

CCS CONCEPTS

• **General and reference** → **Surveys and overviews**; • **Applied computing** → **Imaging**; • **Software and its engineering** → **Virtual worlds software**; • **Human-centered computing** → **Virtual reality**.

KEYWORDS

virtual reality, radiology, systematic literature review

ACM Reference Format:
Renan Trévia and Marcio Sarroglia Pinho. 2021. Virtual Reality in Radiology: A Systematic Mapping Study. In *Symposium on Virtual and Augmented Reality (SVR'21), October 18–21, 2021, Virtual Event, Brazil.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3488162.3488224

1 INTRODUCTION

A potential use for virtual reality (VR) technology in the medical area is to assist radiologists when performing a radiological diagnosis as they usually do it in workstations to analyze the medical data using three-dimensional visualization [15] in traditional 2D desktop displays [32]. Hence, inadequate ergonomic postures and, more importantly, improper room conditions can cause erroneous diagnostics when professionals examine such digital images using common displays [30].

Based on this scenario, the objective of this work is to determine and characterize the state-of-the-art on VR in radiology. To do so, we performed a systematic mapping study [3][5][27] aimed at: (1) discovering the uses, benefits and main barriers of VR in radiology and (2) identifying gaps for future studies.

From an initial set of 329 papers, we have identified 24 primary studies worth analyzing from 6 individual scientific databases.

This work is organized as follows: Section 2 introduces the main area explored in this study. In Section 3 we detail the research methodology, including the presentation of the research questions. We explore the results from the systematic mapping study in Section 4. In Section 5 we present the answers to the research questions. Lastly, Section 6 concludes the paper by describing our final remarks.

2 BACKGROUND

Radiology is a medical discipline in which images visualizing human bodies are examined for abnormalities [8] and radiological studies are undoubtedly one of the most important resources when diagnosing different clinical pathologies, used in different medical specialties [15].

It is remarkable that medical images which are inherently 3D in nature are mostly visualized in clinical practice by physicians and radiology technicians [20] in reading rooms [38], using multiple 2D displays among 1D or 2D input media [6].

When reading 3D images, radiologists need to view and scroll through a substantial number of image slices (a slice is a single 2D image of a cross section of the human body [8]) and manipulate that image in such a manner that abnormalities become visible [8].

Therefore, clinicians have to deal with the presence of external factors such as external lights and screen color saturation when diagnosing, which might interfere with the process [30][32]. Besides, the interpretation of these images is considered a highly complex task since medical images are not self-explanatory [9][35].

3 METHODOLOGY

As stated in Section 1, the goal of this study is to determine and characterize the state-of-the-art on VR in radiology. To do so, we conducted this systematic mapping following the recommendation from influential researchers in the software engineering area [3][5][27].

3.1 Research questions

In order to determine and characterize the state-of-the-art on VR in radiology, the following research questions were defined:

- **RQ1:** How is virtual reality used in radiology?
- **RQ2:** What are the benefits of using virtual reality in radiology?
- **RQ3:** What are the challenges of using virtual reality in radiology?

SVR'21, October 18–21, 2021, Virtual Event, Brazil

ACM ISBN 978-1-4503-9552-6/21/10…$15.00
https://doi.org/10.1145/3488162.3488224

The purpose of RQ1 is to discover the ways VR has been used in radiology and its main techniques and applications. From the following questions (RQ2 and RQ3) we intend to analyze the benefits and the challenges of using VR in radiology in order to find out the reasons it is applied to radiology and the difficulties it may have.

3.2 Data source and search strategy

After defining the research questions, we built up a general string based on Kitchenham et al. [3] guidelines to identify primary studies on electronic databases to answer the research questions. The general string used in this study was: "(virtual reality OR vr) AND (radiology)".

About the inclusion criteria, we decided to select papers from January 2014 to July 2021 in order to get the most recent works in the research area. We also only included papers that were accepted in journals, conferences, workshops, and symposia and were written in English. In addition to that, we excluded duplicated papers, literature only available in the form of abstracts or presentations and publication not related to the field of study.

To start the process of finding primary studies, we performed an initial research on the selected databases using the general string and the inclusion criteria, which yielded 329 studies. Table 1 summarizes the number of papers returned from each database.

Table 1: Returned papers

Database	# Papers
IEEExplore (https://ieeexplore.ieee.org/)	24
ACM Digital Library (https://dl.acm.org/)	3
Engineering Village (https://www.engineeringvillage.com/)	50
ScienceDirect (https://www.sciencedirect.com/)	41
Scopus (https://www.scopus.com/)	168
PubMed (https://pubmed.ncbi.nlm.nih.gov)	43
Total	329

3.3 Keywording, data extraction and mapping

In our study, three main categories were created to classify the studies, these being: contribution category, research type category and computer target category. The contribution category describes the main contribution of the work to the area, and it was created from the keywords found on the keywording process. The options for that category are: diagnostic imaging, medical education, patient care, interaction technique and tool. Furthermore, the research type category reflects the research approach used in the papers. We chose an existing classification of research approach presented by Wieringa et al. [37] and added a new research type called "Overview Paper" to fit the papers that were only reviewing the available content of VR in radiology. Besides, the computer target category details the source of computational power in which the developed solutions aim to be deployed, these being: desktop, smartphone, HMD and CAVE.

4 RESULTS

From an initial set of 329 papers identified through the search strategy (see Section 3.2), we have come across 24 primary studies after applying the exclusion criteria. The systematic map result is presented in Table 2.

About the distribution of the studies according to their computer target category, it is clear that most papers aim traditional computers (desktop) as their main research deployment target, leaving smartphone, CAVE and standalone HMD as possible gaps in the area for further solution development.

In regards to the contribution, it is possible to see that the ones with the highest number of studies throughout the years are diagnostic imaging (DI), medical education (ME) and patient care (PC), with 2018 being the year with the greatest number of papers about DI. There seems to be a gap on interaction techniques and tools when it comes to the contribution.

In the following section we provide details about the 24 studies evaluated.

5 ANALYSIS

In this section we analyze the three research questions proposed for this study. The answers for them came from the information we got in Section 4 combined with the learnings and insights from each of the 24 primary studies selected.

5.1 RQ1. How is virtual reality used in radiology?

The overview of this systematic mapping study detailed in Table 2, indicates that VR has been used in the radiological field among three main areas, those being: diagnostic imaging, medical education, and patient care.

In regard to diagnostic imaging, we have VR radiology reading room that allows imagiologists to focus on the medical image data, while avoiding the conditions that can interfere with radiodiagnostic [32][38]. Moreover, we have the CAVE, an immersive, navigable, and interactive environment for visualizing complex data sets [20].

In addition to that, we also have a multimodal real-time decision support system where radiologists can visualize and interact with patient data in VR by using natural speech and hand gestures [28][39]. In regard to hand gestures, it is interesting to highlight that four studies use Leap Motion Controller[1] as their input system for the developed solution [15][31][32][38]. Besides, a project called NextMed allows radiologists to visualize any anatomical structure of the patient on the table, as well as manipulate and analyze them in 3D as if they were real [15]. Moreover, congenital heart disease data when conjoined with VR has been used to diagnose atrial septal defects [33]. Furthermore, VR has also been used for detection of lung nodules on CT [25].

About medical education, a wide range of uses can be underlined. First, VR technology has been adopted in surgery residency programs to train residents in laparoscopic surgery technique [13]. Furthermore, surgeons are also using VR for making preoperative decisions as the surgical procedure can be planned non-invasively on already existing cross-sectional images [39] and simulated on patient-specific virtual models prior to being performed on the real patient [21]. Moreover, in a study conducted in Spain, computed tomography (CT) was utilized to make 3D models to confirm anatomical compatibility with recipients [12]. Besides, we also have

[1] https://www.ultraleap.com/product/leap-motion-controller/

Table 2: Systematic map result

Author	Year	Research Type	Forum Type	Contribution	Computer Target
Venson et al. [36]	2016	Evaluation Research	Conference	Diagnostic Imaging	Desktop/Smartphone
Sousa et al. [32]	2017	Evaluation Research	Conference	Interaction Technique	Desktop
Klonig et al. [16]	2020	Evaluation Research	Conference	Diagnostic Imaging / Medical Education	N/A
Wirth et al. [38]	2018	Evaluation Research	Symposium	Interaction Technique	Desktop
Liszio et al. [19]	2020	Evaluation Research	Symposium	Patient Care	N/A
Venson et al. [10]	2017	Evaluation Research	Journal	Diagnostic Imaging	Desktop/Smartphone
Nguyen et al. [25]	2018	Evaluation Research	Journal	Diagnostic Imaging	Desktop
Han et al. [14]	2019	Evaluation Research	Journal	Patient Care	HMD
Sapkaroski et al. [31]	2019	Evaluation Research	Journal	Medical Education	Desktop
Sun et al. [33]	2020	Evaluation Research	Journal	Patient Care	N/A
Locuson et al. [20]	2015	Solution Proposal	Conference	Diagnostic Imaging	CAVE
Izard et al. [15]	2018	Solution Proposal	Conference	Diagnostic Imaging	Desktop
Prange et al. [28]	2018	Solution Proposal	Conference	Diagnostic Imaging	Desktop
Xu et al. [39]	2020	Solution Proposal	Conference	Medical Education	Desktop
Knodel et al. [17]	2018	Solution Proposal	Journal	Tool	CAVE
Alsofy et al. [1]	2020	Solution Proposal	Journal	Diagnostic Imaging	N/A
Laas et al. [18]	2021	Solution Proposal	Journal	Medical Education	N/A
Marescaux et al. [21]	2015	Overview Paper	Journal	Medical Education	Desktop
Belmustakov et al. [4]	2018	Overview Paper	Journal	Medical Education	Desktop
Sutherland et al. [34]	2018	Overview Paper	Journal	Diagnostic Imaging / Medical Education / Patient Care	Desktop/Smartphone
McCarthy et al. [22]	2019	Overview Paper	Journal	Medical Education	Desktop/Smartphone
Elsayed et al. [11]	2020	Overview Paper	Journal	Diagnostic Imaging / Medical Education / Patient Care	N/A
Ammanuel et al. [2]	2019	Experience Paper	Journal	Tool	N/A
Abdelrazek et al. [23]	2018	Opinion Paper	Journal	Diagnostic Imaging / Medical Education	N/A

low-cost VR simulations that can help reduce errors and the number of actions in a surgical operation [26]. In addition, VR has been successfully used for resident procedural training, e.g., to simulate lumbar punctures or to better understand complex imaging anatomy, for example, the ultrasound appearance of spinal anatomy [29].

Regarding patient care, VR has emerged as a candidate to treat MRI-related anxiety as for most patients, lying inside the MRI scanner for the average examination time of 20 minutes is an unpleasant, sometimes frightening experience [19]. Furthermore, it can also be used as a tool to teach patients about their health or treatment, or to deliver treatment [14][34]. Beyond that, in the absence of a patient's presence entirely, VR and AR are an interesting clinician tool of intervention planning aid [34].

Lastly, we noticed that VR can also be used as a tool for collaboration as it creates a wide variety of collaborative opportunities. An example of such use would be clinicians and other health care experts inhabit the same virtual space and discuss the same medical data that is either a mutually interactable object in front of them, or the shared virtual environment (VE) itself [34].

5.2 RQ2. What are the benefits of using virtual reality in radiology?

Regarding diagnostic imaging, the use of VR reading rooms could cut equipment and maintenance costs, and by eliminating effects of ambient lighting conditions it could potentially improve diagnostic accuracy [11]. In addition to that, compared to the 3D printed model of the patient specific-anatomy and pathology, VR is a more flexible and inexpensive alternative [10].

Besides, 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, which 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 [10]. Furthermore, Venson et al. [36] demonstrated that VR shows high effectiveness in identifying superficial fractures for two different volume exams.

VR has the potential to augment the possibilities of grasping the complex morphology of anatomical structures or the pathological changes e.g., in cancer or cardiovascular disease. Thereby, medical immersive imaging not only improve diagnostic imaging and surgical procedure planning, but also serve educative purposes for medical students and doctors [17].

About medical education, some VR systems allow surgeons to take completely free perspectives on the anatomical structures from all directions, which provides a much more intuitive understanding of the present situs, and even more of the underlying pathology [1]. Moreover, VR-based visualization of the native MRI grants surgeons an enhanced understanding of tumor localization and breast volumes and it can increase the incidence of breast-conserving surgeries allowing successful oncoplastic procedures [18].

In addition, by using VR, trainees can be transported into a procedure room where they may observe and even participate in virtual procedures before performing them on patients. This allows educators to provide standardized and curated educational training material to all trainees [4][11][31].

Another benefit of using VR equipment for delivering of medical training content is that such content can be reviewed at a time convenient to the learner, thereby decreasing the effort, coordination, resources, and expense associated with hands-on simulation training [7].

Finally, in regard to patient care, VR technology has many advantages over conventional systems for patient entertainment during MRI examinations as it is most capable of distracting patients from the unpleasant sensations of the scanning procedure [19]. Besides, the reported successes of using VR for distraction therapy, during invasive surgical procedures warrants adoption in interventional radiology as well [11]. Patients prone to anxiety, claustrophobia, or high analgesic requirements during interventional radiology procedures may find this therapy especially beneficial [11].

5.3 RQ3. What are the challenges of using virtual reality in radiology?

Although the number of benefits in using VR in the radiological field is quite remarkable, there are many challenges associated with the use of such technology. First, VR poses a challenge for model creators to include sufficient anatomical detail to maintain clinical accuracy while allowing for smooth, real-time interactive visualization [34] as minute structures may be too small to resolve on the 3D reconstruction and VR environment depends on the quality of the original imaging dataset which is susceptible to artifacts secondary to motion and beam hardening [23]. In addition to that, the development of high-quality content requires a degree of technical knowledge that is beyond what an average technology user possesses [22] and creating VR models currently requires the use of multiple software applications at the same time, which can be difficult for the user to learn [2].

Beyond that, regarding the use of VR to reduce MRI-related anxiety, many HMDs are not suitable for it due to their magnetic components which are strongly attracted by the MRI scanner's magnets, hence carrying a high risk of injury [19]. Another problem is the, sometimes considerable, heating of ferromagnetic materials, which can lead to severe burns [19].

Lastly, innovation in healthcare requires strict regulation and high sense of responsibility. Patient safety and quality of life are major issues and, for this reason, innovation in healthcare needs to be patient-centered in order to be effective [21], thus creating a barrier to novel solutions in that area. Besides, as stated by Sousa et al. [32], there is also the physician's resistance to novel systems and technologies. Klonig et al. [16] also mention that the immersion in the VE might increase the emotional gap between physicists and patient, and potentially contributes to objectifying patients.

6 FINAL REMARKS

In this paper we conducted a systematic mapping study in order to identify the main uses of VR in the context of radiology and characterize the benefits and challenges of it. The goal was not only to determine and characterize the state-of-the-art on VR in radiology, but also to create a general understanding of the area and find gaps for future exploration.

After performing the research, we classified the studies according to three categories: contribution, research type and computer target. The contribution category revealed five possible classifications in which the studies fit: diagnostic imaging, medical education, patient care, interaction technique and tools. In addition, computer target category showed four possibilities for papers, these being: desktop, smartphone, CAVE and HMD. Most of the studies in the area are recent and the majority of them were published in journals. Our study also indicates that there are many attempts to insert the VR in radiology.

Regarding the first research question proposed — How is VR used in radiology? — we could identify that it has been used in three major areas: diagnostic imaging, medical education, and patient care. In the diagnostic imaging area, VR has been used to protect physicians from external factors such as room illuminations [10][16][17][20][25][28][32][36][38]. About medical education, VR is being used to allow doctors to review medical data and take preoperative decisions before going to a real surgery [21][39]. In regard to patient care, VR has emerged as a candidate to treat MRI-anxiety [19] and educate patients about their health and treatment [14][34].

The second research question — What are the benefits of using VR in radiology? — the use of VR in radiology cuts the equipment and maintenance costs of a real radiology reading room and it could potentially improve accuracy in radiological diagnosis [11]. Besides, VR also distracts patients in unpleasant radiological procedures [19] and it is also more flexible and unexpensive when compared to 3D printing [10].

From the third research question — What are the challenges of using VR in radiology? — not all VR hardware are suitable for the radiology field as some of them include magnetic components that might prevent them from being used in radiological procedures [19]. Moreover, doctors also present a resistance to novel systems and technologies [32], and VR presents side effects on its use, such as neck pain, nausea, dizziness [24].

In conclusion, this systematic mapping was a first attempt to better understand the context of VR in the radiology field. We understand that several opportunities were created and can be explored from the findings we carried out. We intend to examine the identified gaps in order to develop further research on the proposed topic.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

REFERENCES

[1] Samer Zawy Alsofy, Makoto Nakamura, Christian Ewelt, Konstantinos Kafchitsas, Thomas Fortmann, Stephanie Schipmann, Eric Suero Molina, Heinz Welzel Saravia, and Ralf Stroop. 2020. Comparison of stand-alone cage and cage-with-plate for monosegmental cervical fusion and impact of virtual reality in evaluating surgical results. *Clinical Neurology and Neurosurgery* 191 (April 2020), 105685. https://doi.org/10.1016/j.clineuro.2020.105685

[2] Simon Ammanuel, Isaiah Brown, Jesus Uribe, and Bhavya Rehani. 2019. Creating 3D models from Radiologic Images for Virtual Reality Medical Education Modules. *Journal of Medical Systems* 43, 6 (May 2019). https://doi.org/10.1007/s10916-019-1308-3

[3] Kitchenham BA and Stuart Charters. 2007. Guidelines for performing Systematic Literature Reviews in Software Engineering. 2 (01 2007).

[4] Stephen Belmustakov, Christopher Bailey, and Clifford R. Weiss. 2018. Augmented and Virtual Reality Navigation for Interventions in the Musculoskeletal System. *Current Radiology Reports* 6, 9 (July 2018). https://doi.org/10.1007/s40134-018-0293-5

[5] David Budgen, Mark Turner, Pearl Brereton, and Barbara Kitchenham. 2008. Using Mapping Studies in Software Engineering. *Proceedings of PPIG 2008* 2 (01 2008).

[6] Stuart K. Card, Jock D. Mackinlay, and George G. Robertson. 1990. The design space of input devices. In *Proceedings of the SIGCHI conference on Human factors in computing systems Empowering people - CHI '90*. ACM Press. https://doi.org/10.1145/97243.97263

[7] Todd P. Chang and Debra Weiner. 2016. Screen-Based Simulation and Virtual Reality for Pediatric Emergency Medicine. *Clinical Pediatric Emergency Medicine* 17, 3 (Sept. 2016), 224–230. https://doi.org/10.1016/j.cpem.2016.05.002

[8] Larissa den Boer, Marieke F. van der Schaaf, Koen L. Vincken, Chris P. Mol, Bobby G. Stuijfzand, and Anouk van der Gijp. 2018. Volumetric image interpretation in radiology: scroll behavior and cognitive processes. *Advances in Health Sciences Education* 23, 4 (May 2018), 783–802. https://doi.org/10.1007/s10459-018-9828-z

[9] Trafton Drew, Karla Evans, Melissa L. H. Võ, Francine L. Jacobson, and Jeremy M. Wolfe. 2013. Informatics in Radiology: What Can You See in a Single Glance and How Might This Guide Visual Search in Medical Images? *RadioGraphics* 33, 1 (Jan. 2013), 263–274. https://doi.org/10.1148/rg.331125023

[10] Venson Jose; Eduardo, Albiero Berni Jean Carlo, Edmilson da Silva Maia Carlos, Marques da Silva Ana Maria, Cordeiro d'Ornellas Marcos, and Maciel Anderson. 2017. A Case-Based Study with Radiologists Performing Diagnosis Tasks in Virtual Reality. *Studies in Health Technology and Informatics* 245, MEDINFO 2017: Precision Healthcare through Informatics (2017), 244–248. https://doi.org/10.3233/978-1-61499-830-3-244

[11] Mohammad Elsayed, Nadja Kadom, Comeron Ghobadi, Benjamin Strauss, Omran Al Dandan, Abhimanyu Aggarwal, Yoshimi Anzai, Brent Griffith, Frances Lazarow, Christopher M Straus, and Nabile M Safdar. 2020. Virtual and augmented reality: potential applications in radiology. *Acta Radiologica* 61, 9 (Jan. 2020), 1258–1265. https://doi.org/10.1177/0284185119897362

[12] Jose-Alberto Fernandez-Alvarez, Pedro Infante-Cossio, Fernando Barrera-Pulido, Purificacion Gacto-Sanchez, Cristina Suarez-Mejias, Gorka Gomez-Ciriza, Domingo Sicilia-Castro, and Tomas Gomez-Cia. 2014. Virtual Reality AYRA Software for Preoperative Planning in Facial Allotransplantation. *Journal of Craniofacial Surgery* 25, 5 (Sept. 2014), 1805–1809. https://doi.org/10.1097/scs.0000000000000989

[13] R. L. Friedman and B. W. Pace. 1996. Resident education in laparoscopic cholecystectomy. *Surgical Endoscopy* 10, 1 (Jan. 1996), 26–28. https://doi.org/10.1007/s004649910005

[14] Sung-Hee Han, Jin-Woo Park, Sang Il Choi, Ji Young Kim, Hyunju Lee, Hee-Jeong Yoo, and Jung-Hee Ryu. 2019. Effect of Immersive Virtual Reality Education Before Chest Radiography on Anxiety and Distress Among Pediatric Patients. *JAMA Pediatrics* 173, 11 (Nov. 2019), 1026. https://doi.org/10.1001/jamapediatrics.2019.3000

[15] Santiago González Izard, Juan A. Juanes Méndez, Pablo Ruisoto, and Francisco José García-Peñalvo. 2018. NextMed. In *Proceedings of the Sixth International Conference on Technological Ecosystems for Enhancing Multiculturality*. ACM. https://doi.org/10.1145/3284179.3284247

[16] Johannes Klonig and Marc Herrlich. 2020. Integrating 3D and 2D Views of Medical Image Data in Virtual Reality for Efficient Navigation. In *2020 IEEE International Conference on Healthcare Informatics (ICHI)*. IEEE. https://doi.org/10.1109/ichi48887.2020.9374344

[17] Markus M. Knodel, Babett Lemke, Michael Lampe, Michael Hoffer, Clarissa Gillmann, Michael Uder, Jens Hillengaß, Gabriel Wittum, and Tobias Bäuerle. 2018. Virtual reality in advanced medical immersive imaging: a workflow for introducing virtual reality as a supporting tool in medical imaging. *Computing and Visualization in Science* 18, 6 (Feb. 2018), 203–212. https://doi.org/10.1007/s00791-018-0292-3

[18] Enora Laas, Mohamed El Beheiry, Jean-Baptiste Masson, and Caroline Malhaire. 2021. Partial breast resection for multifocal lower quadrant breast tumour using virtual reality. *BMJ Case Reports* 14, 3 (March 2021), e241608. https://doi.org/10.1136/bcr-2021-241608

[19] Stefan Liszio, Oliver Basu, and Maic Masuch. 2020. A Universe Inside the MRI Scanner: An In-Bore Virtual Reality Game for Children to Reduce Anxiety and Stress. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*. ACM. https://doi.org/10.1145/3410404.3414263

[20] Mark D. Locuson, George D. Lecakes, Anthony Aita, H. Warren Goldman, Shreekanth Mandayam, and Mira Lalovic-Hand. 2015. A virtual scalpel for visualizing patients in a three-dimensional, immersive, navigable and interactive virtual reality environment. In *2015 IEEE Sensors Applications Symposium (SAS)*. IEEE. https://doi.org/10.1109/sas.2015.7133648

[21] Jacques Marescaux and Michele Diana. 2015. Next step in minimally invasive surgery: hybrid image-guided surgery. *Journal of Pediatric Surgery* 50, 1 (Jan. 2015), 30–36. https://doi.org/10.1016/j.jpedsurg.2014.10.022

[22] Colin J. McCarthy and Raul N. Uppot. 2019. Advances in Virtual and Augmented Reality—Exploring the Role in Health-care Education. *Journal of Radiology Nursing* 38, 2 (June 2019), 104–105. https://doi.org/10.1016/j.jradnu.2019.01.008

[23] Mohammed Ahmed Abdelrazek Mohammed, Mohamed H. Khalaf, Andrew Kesselman, David S. Wang, and Nishita Kothary. 2018. A Role for Virtual Reality in Planning Endovascular Procedures. *Journal of Vascular and Interventional Radiology* 29, 7 (July 2018), 971–974. https://doi.org/10.1016/j.jvir.2018.02.018

[24] Christian Moro, Zane Štromberga, and Allan Stirling. 2017. Virtualisation devices for student learning: Comparison between desktop-based (Oculus Rift) and mobile-based (Gear VR) virtual reality in medical and health science education. *Australasian Journal of Educational Technology* 33, 6 (Nov. 2017). https://doi.org/10.14742/ajet.3840

[25] Brian Nguyen, Aman Khurana, Brendon Bagley, Andrew Yen, Richard Brown, Jadranka Stojanovska, Michael Cline, Mitchell Goodsitt, and Sebastian Obrzut. 2018. Evaluation of Virtual Reality for Detection of Lung Nodules on Computed Tomography. *Tomography* 4, 4 (Dec. 2018), 204–208. https://doi.org/10.18383/j.tom.2018.00053

[26] Chung Hyuk Park, Kenneth L. Wilson, and Ayanna M. Howard. 2014. Pilot Study: Supplementing Surgical Training for Medical Students Using a Low-Cost Virtual Reality Simulator. In *2014 IEEE 27th International Symposium on Computer-Based Medical Systems*. IEEE. https://doi.org/10.1109/cbms.2014.74

[27] Kai Petersen, Robert Feldt, Shahid Mujtaba, and Michael Mattsson. 2008. Systematic Mapping Studies in Software Engineering. In *Proceedings of the 12th International Conference on Evaluation and Assessment in Software Engineering* (Italy) *(EASE'08)*. BCS Learning; Development Ltd., Swindon, GBR, 68–77.

[28] Alexander Prange, Michael Barz, and Daniel Sonntag. 2018. Medical 3D Images in Multimodal Virtual Reality. In *Proceedings of the 23rd International Conference on Intelligent User Interfaces Companion*. ACM. https://doi.org/10.1145/3180308.3180327

[29] Reva Ramlogan, Ahtsham U. Niazi, Rongyu Jin, James Johnson, Vincent W. Chan, and Anahi Perlas. 2017. A Virtual Reality Simulation Model of Spinal Ultrasound. *Regional Anesthesia and Pain Medicine* 42, 2 (2017), 217–222. https://doi.org/10.1097/aap.0000000000000537

[30] Ehsan Samei, Aldo Badano, Dev Chakraborty, Ken Compton, Craig Cornelius, Kevin Corrigan, Michael J. Flynn, Bradley Hemminger, Nick Hangiandreou, Jeffrey Johnson, Donna M. Moxley-Stevens, William Pavlicek, Hans Roehrig, Lois Rutz, Ehsan Samei, Jeffrey Shepard, Robert A. Uzenoff, Jihong Wang, and Charles E. Willis. 2005. Assessment of display performance for medical imaging systems: Executive summary of AAPM TG18 report. *Medical Physics* 32, 4 (April 2005), 1205–1225. https://doi.org/10.1118/1.1861159

[31] Daniel Sapkaroski, Marilyn Baird, Matthew Mundy, and Matthew Richard Dimmock. 2019. Quantification of Student Radiographic Patient Positioning Using an Immersive Virtual Reality Simulation. *Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare* 14, 4 (July 2019), 258–263. https://doi.org/10.1097/sih.0000000000000380

[32] Maurício Sousa, Daniel Mendes, Soraia Paulo, Nuno Matela, Joaquim Jorge, and Daniel Simões Lopes. 2017. VRRRRoom. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM. https://doi.org/10.1145/3025453.3025566

[33] K. Sun, H.H. Xue, J.G. Yu, J. Wang, G.Z. Chen, W.J. Hong, and W.Q. Wang. 2005. A primary exploration of three-dimensional echocardiographic intra-cardiac virtual reality visualization of atrial septal defect: in vitro validation. In *Computers in Cardiology, 2005*. IEEE. https://doi.org/10.1109/cic.2005.1588055

[34] Justin Sutherland, Jason Belec, Adnan Sheikh, Leonid Chepelev, Waleed Althobaity, Benjamin J. W. Chow, Dimitrios Mitsouras, Andy Christensen, Frank J. Rybicki, and Daniel J. La Russa. 2018. Applying Modern Virtual and Augmented Reality Technologies to Medical Images and Models. *Journal of Digital Imaging* 32, 1 (Sept. 2018), 38–53. https://doi.org/10.1007/s10278-018-0122-7

[35] A. van der Gijp, M. F. van der Schaaf, I. C. van der Schaaf, J. C. B. M. Huige, C. J. Ravesloot, J. P. J. van Schaik, and Th. J. ten Cate. 2014. Interpretation of radiological images: towards a framework of knowledge and skills. *Advances in Health Sciences Education* 19, 4 (Jan. 2014), 565–580. https://doi.org/10.1007/s10459-013-9488-y

[36] Jose E. Venson, Jean Berni, Carlos S. Maia, A. Marques da Silva, Marcos d'Ornelas, and Anderson Maciel. 2016. Medical imaging VR. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*. ACM. https://doi.org/10.1145/2993369.2996333

[37] Roel Wieringa, Neil Maiden, Nancy Mead, and Colette Rolland. 2005. Requirements engineering paper classification and evaluation criteria: a proposal and a discussion. *Requirements Engineering* 11, 1 (Nov. 2005), 102–107. https://doi.org/10.1007/s00766-005-0021-6

[38] Markus Wirth, Stefan Gradl, Jan Sembdner, Soeren Kuhrt, and Bjoern M. Eskofier. 2018. Evaluation of Interaction Techniques for a Virtual Reality Reading Room in Diagnostic Radiology. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. ACM. https://doi.org/10.1145/3242587.3242636

[39] Xuanhui Xu, Eleni Mangina, David Kilroy, Kathleen M. Curran, John J. Healy, and Abraham G. Campbell. 2020. Doctoral Colloquium—A Snapshot of the Future: Virtual and Augmented Reality Training for Radiology. In *2020 6th International Conference of the Immersive Learning Research Network (iLRN)*. IEEE. https://doi.org/10.23919/ilrn47897.2020.9155131