Supplementary material

s.1 ANDJ checklist

Section/topic	#	Checklist item	Reported on page TO BE UPDATED BASED ON THE TEXT CHANGES during the peer review
TITLE			
title	1	Identify the report as a Narrative Review of …	**Pag. 1**
ABSTRACT			
	2	Provide an unstructured summary including, as applicable: background, objective, brief summary of narrative review and implications for future research, and clinical practice or policy development.	**Pag. 1**
INTRODUCTION			
Rationale/background	3	Describe the rationale for the review in the context of what is already known.	**Pag. 1-11**
Objectives	4	Specify the key question(s) identified for the review topic.	**Pag. 11**
METHODS			
Research selection	5	Specify the process for identifying the literature search (eg, years considered, language, publication status, study design, and databases of coverage).	**Pag. 11-12**
DISCUSSION/SUMMARY			
Narrative	**6**	Discuss: 1) research reviewed including fundamental or key findings, 2) limitations and/or quality of research reviewed, and 3) need for future research.	**Pag. 12-34**
Summary	**7**	Provide an overall interpretation of the narrative review in the context of clinical practice for health professionals, policy development and implementation, or future research.	**Pag. 26-36**

Table. S 1 ANDJ checklist

s.2. In-Depth Analysis of the Detected Studies: A Comprehensive Overview

To complement our overview, after having identified the themes and focus elements of the studies, we report here a more far-reaching summary of each individual study.

Sutherland et al. [81] describes the growth of VR and AR in medicine (with the focus on radiology) and the transition from primarily patient-oriented applications to wider use by clinicians. Published in 2019, this review examines the limitations of the technology that have so far hindered clinical application due to insufficient quality, as well as the definitions of VR and AR, their development history, and discusses consumer-level systems, technical considerations for clinical integration, and an overview of medical VR/AR applications. A comprehensive framework for processing medical images in VR and AR is presented and its integration into radiological workflows and applicability in different clinical contexts is proposed.

Elsayed et al. [82] deals with importance of the potential of VR and AR to contribute in clinical practice and in radiologists practice. These technologies promise to transform clinical imaging applications and radiology practice This recent review provides an overview of VR and AR, current applications, future developments, the challenges to their broader adoption in digital imaging.

The systematic review proposed by Gelmini et al. [83] aimed to compare the effectiveness of VR simulations with traditional teaching methods in interventional radiology education. A comprehensive search of multiple databases, including Cochrane Library, PubMed, Embase and others, identified studies for inclusion based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses and the Best Evidence Medical Education guidelines. The assessment of quality and eligibility led to the review of five randomized clinical trials whose effects were measured using the Kirkpatrick model and which had a mixture of level 2B and 4B outcomes. These studies consistently suggest that VR improves learning in interventional radiology through the effective integration of concepts. Despite the proven effectiveness of VR in skill acquisition, there is a lack of research on the standardization of VR use across procedures in this area, highlighting the need for further study.

The recent review by von Ende et al. [84] examines in the VR integration in radiology the role of AI, including its subset of machine learning, in the field of medicine by processing and interpreting data through complex algorithms, mimicking or surpassing the cognitive abilities of humans. The integration of AI in augmented reality, VR and radio genomics promises to improve the efficiency and accuracy of radiological diagnosis and treatment planning. However, the application of AI in interventional radiology faces obstacles that limit its clinical acceptance. Despite these challenges, the field is poised for exponential growth due to ongoing advances in machine learning and deep learning. This review explores current and future AI applications in interventional radiology and the challenges and limitations that need to be addressed for wider clinical adoption.

Gamba et al. [85] examines the current technology and future applications of VR and AR in digital radiology imaging. In particular, this work shows that the technologies are increasingly recognized for their potential to improve medical education and healthcare, especially in radiology. These technologies have shown promise in transforming radiology workspaces, such as the traditional reading room, into more dynamic and interactive environments through VR software. However, research on VR-simulated radiology workstations is still in its infancy and there are few studies on their potential applications. This review examines the current status and practical benefits of VR reading room technology for radiologists and learners, and finds that further research is needed to fully understand

its benefits and overcome the barriers to adoption. It emphasizes the technology's potential to innovate radiological practice and urges further investigation to promote its development and integration into healthcare.

Chytas et al. [86] investigates the impact of integrating VR into radiology and anatomy education, a strategy that is increasingly being used. Through a systematic search of databases such as PubMed and SCOPUS, the study aimed to evaluate the effectiveness of VR in improving anatomy education through radiology. Seven selected studies included a mix of comparative and non-comparative research focusing on both academic performance and student perceptions. The results showed that the use of VR in education was consistently well received and demonstrated its effectiveness in improving anatomy knowledge. The positive results highlighted in this study suggest that VR can significantly enhance the teaching of radiology in anatomy courses and encourage educators to utilize this technology.

The review of Iannessi et al. [87] explores the development and potential of computer user interfaces (UI) in radiology with the introduction of VR, a field that is increasingly intertwined with digital imaging. Despite advances, the mouse and keyboard dominate due to their ease of use. This paper evaluates various UIs, including touchscreens, kinetic sensors, eye-tracking and augmented/VR, particularly with regard to their application in two- and three-dimensional imaging in interventional radiology. The study emphasizes the importance of designing UIs specifically for radiologists in order to meet professional requirements and ensure acceptance. It emphasizes the need for good usability and suggests that next-generation UIs must meet the specific requirements of radiology and offers insights into the future direction of UI development in medical imaging.

Gurgitano et al. [88] look at the transformative impact of VR integrated with AI in radiology, tracing the roots of AI back to the 1950s with the development of artificial neural networks and their evolution into sophisticated computerized learning models. Through machine learning and deep learning, AI is able to analyses huge data sets and recognize patterns and insights that go far beyond human capabilities. This innovation is particularly important for radiologists as it improves diagnostic accuracy, treatment customization and resource management. The study also addresses the synergy between AI and technologies such as AR and VR, have the potential to improve the accuracy of minimally invasive treatments. AI algorithms, can rapidly process extensive medical data and identifying intricate patterns, have become essential tools in guiding healthcare procedures. When combined with AR and VR technologies, these AI-driven insights can be visually presented in real-time, providing surgeons with potential useful guidance and "support" their decision-making during minimally invasive surgeries. AR overlays digital information from radiology domains onto the surgeon's field of view, enabling precise anatomical mapping and navigation within the patient's body. By superimposing AI-generated data onto the surgical environment, AR enhances surgeons' understanding of the patient's anatomy, with the potential of more accurate targeting of affected areas and reducing the risk of unintended damage. Similarly, VR creates immersive simulated environments that replicate surgical scenarios, offering a platform for training, preoperative planning, and rehearsing complex procedures. By integrating AI algorithms into VR simulations, healthcare professionals can access personalized training modules tailored to their expertise levels, fostering continuous improvement in minimally invasive techniques.

Beyond diagnostics, the applications of AI in interventional radiology (IR) also extend to patient screening, treatment planning, navigation and education. This points to a future where AI not only complements, but significantly enhances radiology and patient care, pending rigorous investigation and validation.

In 2004, Dankelman et al. [89] investigated the potential role of VR in the training of interventional radiologists, addressing the increasing complexity of procedures and the need for more *specialized* training. Traditional training methods, such as learning during diagnostic angiography, were already becoming less practical due to the emergence of

alternative diagnostic techniques. The paper discusses alternatives such as animal training, bench models and VR, highlighting the respective challenges such as ethical concerns, high costs and difficulties in performance assessment. VR training proves to be a promising solution as it provides a realistic, cost-effective training environment without the limitations of other methods. However, the effectiveness of VR in IR training had not yet been sufficiently researched. In this paper, Rasmussen's model of human behavior is presented to evaluate the potential of VR training for the specific needs and objectives of IR education and to propose a thoughtful approach for the development of future training methods.

Kukla et al. [90] propose a literature review on the use of ER (including VR) in diagnostic imaging and examine its application over the last decade in various modalities such as ultrasound, interventional radiology and computed tomography. The review highlights the role of ER in improving patient positioning, medical education and potentially reducing the need for anesthesia and sedation by improving the patient experience during the examination. The use of ER in medical education, particularly in anatomy and patient positioning, was emphasized for its interactive benefits, although questions remain about cost-effectiveness. The results suggest that ER has a positive impact on clinical practice by enhancing diagnostic capabilities and educational outcomes. However, despite the obvious benefits and potential of ER to increase the accuracy and efficiency of diagnostic procedures, the report calls for further research to overcome the challenges associated with clinical integration and to fully realize the potential of ER in healthcare.

Patel et al. [91] reviews the shift to virtual interviews in residency programs due to COVID-19 pandemic and explore the challenges and opportunities this presents for both applicants and programs. Strategies are discussed on how applicants can present themselves effectively, how programs can assess candidates and how both parties can learn from each other in a virtual environment. The review also looks at optimizing interviews and highlights the importance of preparation, technology and adapting to new formats for interaction and assessment in the residency selection process. The VR here is considered an important educational requirement.

Ravindran's review article [92] looks at advances in managing difficult airways (DA), highlighting innovations in prediction tools, diagnostics such as ultrasound, MRI and CT scans, as well as virtual endoscopy and 3D printing. The article looks at new airway devices, compliance with Difficult Airway Society (DAS) and ASA guidelines and the vortex approach. It also covers novel oxygen supplementation techniques, the use of Anaesthesia Information Management Systems (AIMS), Clinical Decision Support (CDS) systems and the impact of technologies such as VR on DA training and patient counselling, significantly improving clinical standards and patient safety.

Guimarães et al. [93] evaluate the evolving pedagogical trends in medical education, particularly in anatomy, due to advances in science and technology, using 3D images from radiology. This paper discusses the shift towards a model of vertical integration in which basic and clinical sciences coexist, necessitating new technology-based teaching approaches. Traditional anatomy education, which relies primarily on cadaver dissection, is shifting towards 3D modelling and digital imaging, supported by learning management systems and computer-assisted learning. The potential future role of AI, VR and learning analytics in enabling personalized learning processes in real time is highlighted. This shift towards a blended learning approach that integrates multiple pedagogical strategies is seen as essential to tackle the complexity of medical education.

Zhao et al. [94] investigate the development of functional and anthropomorphic models for surgical training in interventional radiology, focusing on the transition from traditional training methods to the use of realistic anatomical phantom models. These models, created through advances in materials technology, offer a safer and more cost-effective training alternative mimicking multi-layer tissue structures. The study examines a large number of articles (*n=189*) published between 2015 and 2020 and analyses the tech-

nical specifications and applications of these phantom models, categorized by manufacturing methods and the organs they simulate. It highlights the importance of gel-based and 3D printing methods in the development of these prototypes, while discussing current challenges and future research directions.

The scoping review by McBain et al. [95] examines the role of ER with a particular focus on AR in anatomical education using 3D medical radiology sources, focusing on its application at different levels of medical training and the assessment tools used to evaluate the different modalities. Analyzing findings from 54 articles, four primary AR modalities were identified: head-mounted displays, projection, instruments and screens, and mobile devices. The review assesses the usability, feasibility and acceptability of these modalities using various assessment tools. It emphasizes the need for further research on the effects of AR on visuospatial skills, cognitive load and academic performance and advocates for studies with robust designs and validated assessment tools to better understand the educational value of AR.

The literature review by Singhal et al. [96] focuses on the fields of oral medicine, radiology, surgery and pathology and emphasizes the importance of understanding the benefits and limitations of these technologies for effective integration into dental practice. The study emphasizes the significant impact of technological advances on dentistry, including tele-dentistry, AI, VR, AR, ER, mixed reality and 3D printing. These innovations have the opportunity to improve the diagnosis, the treatment planning, surgical procedures, prosthetic fabrication and patient care, promising a future with better access to dental care and shorter treatment times. benefits and limitations of these technologies for effective integration into dental practice.

Dammann's review [97] on image processing in radiology, published in 2002, shows significant advances in medical image analysis and its clinical applications. It covers preprocessing algorithms to improve image quality, three-dimensional visualization for data evaluation, registration techniques for merging examination modalities and segmentation methods for structure extraction. These advances have enabled automated quantification, treatment planning, simulation and intervention guidance using medical modelling, VR, surgical robots and navigation systems. The article highlights the need for specialized skills in the production and post-processing of radiological images and points to changing roles for traditional specialties in radiology.

The paper by ter Haar Romeny et al. [98], published in 1998, provides an overview of advances in diagnostic 3D radiology and highlights the role of modern 3D rendering software and computer vision techniques in improving diagnostic imaging and anatomy visualization. This review analyses the sequential process of data preparation, image processing and segmentation that leads to 3D rendering through techniques such as ray casting. The article discusses the integration of data sets from different modalities, the colour coding of functional data and the interactive processing of 3D images facilitated by affordable modern workstations. These developments support applications such as the automatic detection of optimal viewing angles for aneurysms and the simulation of stent insertion and thus have a significant impact on the field of radiology and anatomical training.

Rooney et al. [99] evaluates the use and scope of SBME in radiation oncology, emphasizing its role in competency-based assessment educational goals. This systematic review explores a range of SBME techniques, including virtual and screen-based simulators, showcasing their ability to target various skill sets such as clinical decision-making, contouring, and treatment planning. Through their examination of 54 published articles, they discover that SBME not only met educational objectives but also enhanced competency-based assessment. The findings of the study suggest that the integration of SBME into radiation oncology training programs could yield significant benefits. However, for widespread implementation, improved reporting standards and centralized utilization of SBME resources are essential.

The systematic review by Alvarez-Lopez et al. [100] focuses on the use of commercial off-the-shelf (COTS) devices for detecting manual gestures in surgery, particularly their application as simulation tools for motor and technical skills teaching in minimally invasive surgery (MIS). Microsoft Kinect and Leap Motion Controller are highlighted as the most utilized COTS devices, primarily for image manipulation in surgical and IR environments. Despite the technology's potential for creating portable, low-cost simulators for MIS skills learning, the field remains exploratory, especially in environments requiring sterile conditions. The study suggests a future where COTS devices could facilitate widespread training and pre-surgical preparation.

s.3. In-Depth Analysis of the COTS analyzed in ref. 100

- The Microsoft Kinect (MK) is a motion-sensing input device initially designed for the Xbox gaming console. It employs depth-sensing cameras and infrared projectors to track users' movements in three-dimensional space. Adapted for various applications, including surgical settings, the Kinect serves as a cost-effective sensor capable of tracking surgeons' gestures and movements without requiring direct physical contact with input devices. This functionality makes the Kinect invaluable for controlling robotic systems, such as surgical robots, enabling surgeons to manipulate instruments, interact with virtual interfaces, or navigate through medical imaging data through hand gestures or body movements, thereby enhancing precision and efficiency in surgical procedures.

- Similarly, the Leap Motion Controller (LMC) is a compact, USB-connected device equipped with infrared sensors and cameras, enabling high-precision tracking of hand and finger movements in three-dimensional space. Similar to the Kinect, the LMC functions as an input device for controlling robotic systems. In the domain of robotic surgery, the LMC facilitates tracking of surgeons' hand movements, enabling interaction with virtual interfaces, manipulation of medical images, or control of robotic instruments through intuitive gestures, thereby streamlining surgical workflows and enhancing precision.

- In contrast, the Myo armband is a wearable device featuring electromyography (EMG) sensors embedded in the band, enabling the measurement of muscle activity and gestures. While not a conventional robotic device, the Myo armband serves as an interface for controlling robotic systems or interacting with virtual environments using hand and arm gestures. In surgical contexts, the Myo armband empowers surgeons to manipulate medical images, control robotic instruments, or navigate virtual interfaces seamlessly through intuitive gestures, eliminating the need for physical touch and enhancing overall surgical control and precision.

While these devices may not possess the traditional characteristics of robots, such as mechanical limbs or autonomous movement, their role in enabling gesture-based control and interaction with robotic systems in surgical settings justifies their classification as robotic devices. They serve as crucial interfaces between surgeons and robotic components, facilitating precise control and manipulation during surgical procedures, thereby enhancing patient outcomes and surgical efficiency.