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Review

Radiological Crossroads: Navigating the Intersection of Virtual Reality and Digital Radiology through a Comprehensive Narrative Review of Reviews

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Abstract: The integration of Virtual Reality with radiology is the focus of this study. A narrative review has been proposed to delve into emerging themes within the integration of Virtual Reality in radiology by scrutinizing reviews gathered from PubMed and Scopus. The proposed approach was based on a standard narrative checklist and a qualification process. The selection process identified 20 review studies. Integration of Virtual Reality (VR) in radiology offers potential transformative opportunities also integrated with other emerging technologies. In medical education, VR and AR, using 3D images from radiology, can enhance learning, emphasizing the need for standardized integration. In radiology, VR combined with Artificial Intelligence (AI) and Augmented Reality (AR) shows promising prospectives to give a complimentary contribution to diagnosis, treatment planning, and education. Challenges in clinical integration and User Interface design must be addressed. Innovations in medical education, like 3D modeling and AI, has the potential to enable personalized learning, but face standardization challenges. While robotics play a minor role, advancements and potential perspectives are observed in neurosurgery and endovascular systems. Ongoing research and standardization efforts are crucial for maximizing the potential of these integrative technologies in healthcare. In conclusion, the synthesis of these findings underscores the opportunities for advancements in digital radiology and healthcare through the integration of VR. However, challenges exist, and continuous research, coupled with technological refinements, is imperative to unlock the full potential of these integrative approaches in the dynamic and evolving field of medical imaging.

Keywords: virtual reality; augmented reality; robotics; radiology; artificial intelligence

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1. Introduction

1.1. Virtual Reality's Transformative Role in Healthcare: An Introduction

Virtual Reality (VR) has seamlessly integrated into the healthcare landscape for several years, exerting a dynamic influence across a myriad of sectors [1]. Its impact spans from the potential to improve surgical procedures and enhance radiological practices to playing a pivotal role in both motor and psychological rehabilitation, extending its reach even into specialized fields like dentistry [2]. This transformative contribution is not only confined to day-to-day clinical operations, but is also profoundly reshaping the landscape of medical training [3]. In the current landscape, the fusion of VR with robotics across diverse application domains, coupled with the incorporation of Augmented Reality (AR) [4,5], signifies a compelling evolution in healthcare technologies.

The heightened interest and recognition of the potential of VR and AR have led the Food and Drug Administration (FDA) to categorize them as integral medical devices [6,7]. For example, AR devices are already in use, projecting diagnostic and anatomical images directly onto a patient's surface within the operating room. The FDA maintains an updated catalogue of cutting-edge AR and VR devices on its website [6,7], showcasing their applications across a spectrum from physiotherapy to simulated learning, and from providing support during surgical procedures to facilitating the analysis of intricate radiological images.

Within this landscape, certain devices have the capability to record intricate eye movements, concurrently delivering auditory and visual stimuli. This not only aids medical professionals in the diagnosis of neurological or vestibular disorders, but also represents a groundbreaking approach to medical assessment. Furthermore, there are devices specifically engineered to address visual impairments such as "lazy eye" or amblyopia, prevalent among children. These conditions, characterized by a reduction in visual acuity in one eye without overt pathological signs, are tackled through the strategic deployment of virtual reality headsets that project specially crafted videos, aiming to stimulate and encourage the usage of the "lazy eye" for more effective treatment [8]. This innovative intersection of virtual reality and healthcare showcases the potential to transform diagnostic and therapeutic approaches, marking a paradigm shift in the medical landscape.

1.2. Virtual Reality and Radiology: Exploring Related Studies to Formulate Hypotheses and Research Directions

1.2.1. Radiology Meets Digital Health: A Seamless Blend

Radiology has undergone a transformative evolution thanks to the digitization processes driven by the Digital Imaging and Communications in Medicine (DICOM) standard [9]. Over the years, the evolution of radiology has significantly eased its integration into the broader landscape of Digital Health. This transition marks a fundamental shift from the analogic to the digital field, where radiology increasingly finds itself intertwined with the vast array of possibilities offered by digitalization processes. This integration, driven by the swift standardization of DICOM in radiology—unlike in fields like digital pathology [10], where DICOM adoption lagged (the specialized DICOM for digital pathology, DICOM Whole Slide Image [11], has had a much longer release time and a more articulated adaptation of the manufacturers [10,12])—has been instrumental in expanding data exchange capabilities. Additionally, it has broadened the scope of applications, incorporating emerging technologies. Moreover, it has been pivotal in fostering the expansion of remote diagnostics, particularly evident in the field of teleradiology [13,14]. Furthermore, advancements in technology have led to the development of increasingly miniaturized voxels compared to the rudimentary CT applications of the 1970s, further propelling the integration of radiology into the digital landscape. All of this has facilitated the integration with other technologies, such as VR technologies [15].

This integration, facilitated through DICOM, has been instrumental in fostering seamless communication and integration among various diagnostic imaging systems, thanks to the adoption of Picture Archiving and Communication Systems (PACS). This interoperability extends across diverse imaging modalities, encompassing not only systems reliant on ionizing radiation imaging processes, but also those leveraging alternative techniques such as nuclear magnetic resonance or ultrasound.

The integration, primarily spearheaded by radiology, is often referred to as "digital radiology", particularly concerning the comprehensive storage of all images, including those not strictly of a radiological nature. For instance, Radiology Information Systems (RIS) play a crucial role in managing not just computed tomography (CT) and radiography images, but also those generated through magnetic resonance imaging (MRI) scans and others.

However, it is worth noting that the term "digital radiology" sometimes extends, albeit improperly, beyond radiological systems within hospital contexts. This expansion occurs because these systems rely on shared data storage and management processes (PACS, RIS) that have been inherited from the historical development of radiology. Consequently, even non-radiological imaging data becomes part of this integrated digital framework.

These integrated systems serve as the foundation for a comprehensive array of processing tasks, ranging from diagnostic analyses to the intricate planning of radiotherapeutic treatments. Such treatment planning heavily relies on the precise delineation of volumes and areas, which are meticulously identified through the imaging data provided by these systems.

1.2.2. Digital Radiology Meets Virtual Reality: Proposing Hypotheses and Research Avenues

Regarding the details of VR applications in radiology, various areas of interest have been delineated, with a history dating back to 1994 [16], when the first applications of VR were more associated with the 3D rendering (an interpretation of the concept of VR that has endured over time, maintaining its relevance and validity despite technological advancements and changes in the digital application landscape). The significant impact of digital radiology in this field, as highlighted by a reasoning similar to the previous one, is reported in [17], emphasizing how digital radiology, in its extended sense, providing 3D images, also plays a significant role in other disciplines for which it is an indispensable support (e.g., surgery, orthopedy, oncology treatment, and many others). This study [17] not only reaffirms the pivotal role of radiology in this context, but also identifies the potential development directions, as outlined in Table 1.

Table 1. Emerging topics based on the study by Javaid et al. [17].

Topic	Examples
Advancing Radiologist Expertise	Acts as a mentorship tool for students, enhancing training and learning. Provides immersive virtual simulations for diagnostic experience. Facilitates knowledge acquisition of innovative procedures, improving preclinical skills for patient safety.
Promoting Disease Awareness	Utilizes VR to help illustrating to a patient a medical problem/disease. Offers a comprehensive view for enhanced training and surgical planning. Enables virtual surgical planning for deeper understanding. Enhances patient interaction by sharing information from each visit. Drives awareness of emerging diseases through technology.
Enhancing Patient Relaxation	VR serves as a therapeutic solution for patient relaxation in medical scenarios. Expedites physical therapy, contributing to effective recovery. Alleviates stress through immersive VR experiences. Customizable virtual environments reduce stress during treatment.
Streamlining Healthcare Expenditure	Reduces overall treatment costs and shortens hospital stays. Lowers expenses in designing medical products. Provides a secure environment for medical professionals, reducing management costs.
Innovating Medical Imaging Inspection	VR enables thorough inspection of medical images, expediting analysis. Introduces innovative methods for reviewing and analyzing imaging data. Offers insights for clinical research, creating a conducive learning environment.
Improve the Access to Patient Images	Radiologist have the opportunity to interact with images presented in a 3D format. Enhances understanding of patient anatomy. Visualizes complex structures, aiding in accurate diagnoses.
Crystal Clear Visualization of Blood Vessels	Provides a 3D representation of blood vessels with an interactive opportunity to interact (rotate/zoom/pan, etc.) Inspects heart vessels, contributing to improved surgeries. VR simulation enhances learning opportunities.
Telemonitoring for Remote Healthcare	VR is crucial for remotely monitoring patients. Digitally visualizes real-time information for daily medical procedures. Enables remote-assisted treatment, establishing virtual therapy.

Table 1. *Cont.*

Topic	Examples
Strategic Preoperative Planning	VR plays a crucial role in preoperative planning. Regular patient screenings aid in early identification of potential causes. Utilized for precise planning of surgeries, contributing to improved patient care.
Identifying Patient Abnormalities	VR has the potential to provide information in a complimentary format that would be useful to be integrated with the other ones used for the diagnosis. Enhanced imaging capabilities enable preliminary analysis. Contributes to identifying symptoms of mental health disorders.
Tumor Analysis for Informed Treatment	VR assists in analyzing tumor size, providing insights for effective chemotherapy. Delivers precise information regarding tumor levels. Beneficial for successful clinical trials, allowing for detailed analysis.
Facilitating Informed Decision-Making	VR presents patient information in 3D, aiding well-informed decisions. Enhances comfort for both doctors and patients. Improves patient understanding of procedures and treatment processes.
Optimizing Interventional Radiology (IR) Treatments	VR enhances the efficiency of interventional radiology treatments. Applied in invasive procedures for various cancer treatments, reducing pain and recovery time. Guides medical treatment with minimum risk through real-time virtual video.

This drive for integration leads to an increasingly thorough exploration of emerging needs, spanning regulatory requirements, training, organizational aspects of work, and technological prerequisites [18,19].

1.2.3. Virtual Reality in Radiology: Technological Components, Integration towards Extended Reality, and the Contribution of COVID-19 to Research Expansion

Technological Components and Integration towards Extended Reality

The concept of VR is incredibly expansive and inclusive, encapsulating a spectrum of definitions that underscore its diverse applications. From rudimentary computer-generated 3D reconstructions to immersive navigational experiences powered by cutting-edge technology, VR encompasses a wide array of possibilities. According to Cambridge Dictionary, VR is defined as "a set of images and sounds, produced by a computer, that seem to represent a place or a situation that a person can take part in" (https://dictionary.cambridge.org/it/dizionario/inglese/virtual-reality) (accessed on 15 April 2024) [20]. This definition paints a picture of immersion where users feel deeply engaged in simulated environments, blurring the lines between reality and virtuality.

Building upon this notion, Collins Dictionary elaborates that VR constitutes "an environment which is produced by a computer and seems very like reality to the person experiencing it" (https://www.collinsdictionary.com/it/dizionario/inglese/virtual-reality) (accessed on 15 April 2024) [21]. This description emphasizes the striking realism of VR environments, suggesting that users perceive them with a heightened sense of presence, akin to their experiences in the physical world.

For a more technical perspective, Merriam-Webster characterizes VR as "an artificial environment experienced through sensory stimuli (such as sights and sounds) provided by a computer, where one's actions partially determine what unfolds within the environment" (https://www.merriam-webster.com/dictionary/virtual%20reality) (accessed on 15 April 2024) [22]. This definition underscores the interactive nature of VR, highlighting how users' movements and interactions shape their experiences within virtual realms.

Together, these definitions underscore the vast potential of VR technology, spanning from basic simulations to deeply immersive environments driven by sensory feedback. This breadth showcases the versatility of VR across various domains, including its transformative impact on fields such as radiology.

Based on Jvaid et al. [17], VR has the potential to transform the radiology field by enhancing the capability to provide digital images for intervention guidance, medical training, and education. Radiologists can analyze complex medical conditions with greater precision through 3D imaging of diseased body parts or entire anatomical structures using VR. This transformative technology allows for the visualization of tissues, organs, vessels, and abnormalities in a 3D format, providing a deeper understanding of human anatomy [17,23–25], also transforming datasets into interactive virtual images that behave like holograms [17]. Through VR, it is possible to propose real-time holographic displays of 3D images, allowing radiologists to visualize internal body structures in three dimensions [26,27].

Therefore, various types of technologies can be identified, including Non-immersive Virtual Reality, Fully Immersive Virtual Reality, Semi-Immersive Virtual Reality, Augmented Reality, and Collaborative VR, offering extensive applications in radiology, catering to diverse clinical needs [17,28,29].

Thanks to these technologies, based on the study reported in [17], there is the potential to provide significant support to the world of radiology in its various integrations in the *healthcare domain*. For example:

- In surgical settings, VR has the potential to enhance surgical precision and collaboration among radiologists and specialists, benefiting procedures like ophthalmology, microsurgeries, and neurosurgery [30–32].
- 3D computer-generated images accessible through wearable devices can be utilized in VR, transitioning from entertainment to essential tools in healthcare [33,34].
- Advanced training and diagnosis solutions can be provided, supporting active learner participation, and enabling real-time patient support [35,36].
- Advanced training programs for staff and VR tools can be integrated into patient care workflows, enhancing staff capability and confidence [37,38].

It should be noted that the integration of Virtual Reality into radiology, the true focus of this proposed study, is often accompanied by the integration of other forms of "artificial reality", such as Augmented Reality, to the extent that Virtual and Augmented Reality (VAR) is often mentioned. Recently, as an extension of this concept, Extended Reality (ER), also referred to with the acronym XR, has been discussed.

For Augmented Reality, the spectrum of definitions is broad and can encompass various sectors based on the technologies utilized. The approach of augmented reality is different from that of Virtual Reality, as it aims to maintain a direct relationship with physical reality by adding informational content obtained from digital processing. The following definition remarks just this: "an enhanced version of reality created by the use of technology to overlay digital information on an image of something being viewed through a device (such as a smartphone camera)" (https://www.merriam-webster.com/dictionary/augmented%20reality) (accessed on 15 April 2024) [39].

XR, then, is a further new frontier that has been defined as an umbrella term encompassing VR, AR, and Mixed Reality (MR) [40] (Figure 1). As highlighted in [40], these technologies differ regarding the user's ability to interact with the simulated environment and the degree of reality enhancement. Augmented reality (1) involves adding digital information to the real world, which the user can still see and interact with. In medicine, AR can be used for guidance during procedures by superimposing both virtual and real images into the environment in real-time [41,42]. Smartphone games, for example, commonly use this technology, such as in "Pokemon Go" (Niantic, Inc., San Francisco, CA, USA) or "The Witcher: Monster Slayer" (Spokko Inc., Warsaw, PL, USA). MR (2) combines digital and natural elements to create a new environment with which the user can interact in real-time [43]. Virtual Reality (3), the most well-known form of ER, creates an entirely immersive digital environment that replaces the real world [44]. It can also be used to provide a platform for remote training activities and scientific gatherings.

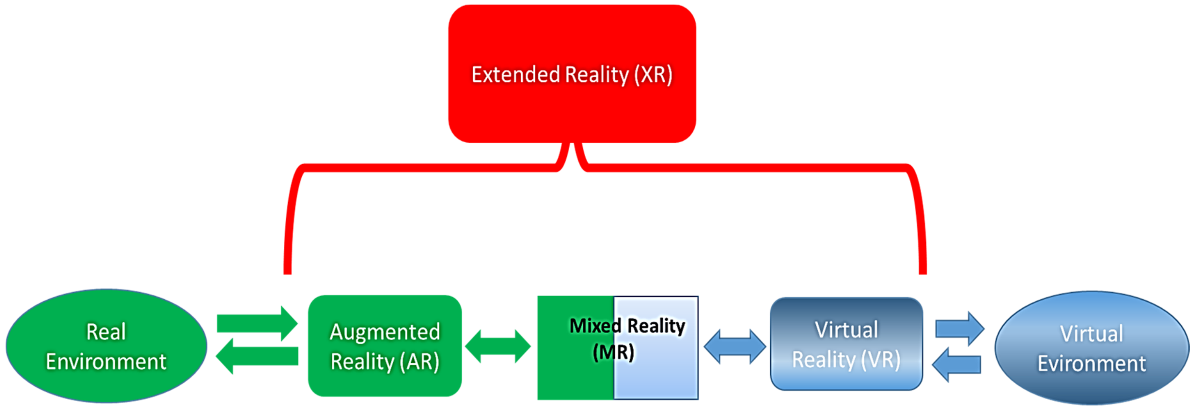

Figure 1. Enhanced graphical depiction illustrating the interaction between VR/AR/MR/XR environments and the virtual as well as the real environment.

For the ultimate VR and MR interaction experience, a head-mounted device (https://www.sciencedirect.com/topics/engineering/head-mounted-device) (HMD) (accessed on 15 April 2024) [45] or a cave automatic virtual environment (https://www.techtarget.com/whatis/definition/CAVE-Cave-Automatic-Virtual-Environment) (CAVE) (accessed on 15 April 2024) [46] is essential. These technologies enable complete immersion in the virtual environment by blocking out the real world and displaying visualizations [47,48]. This distinction is frequently observed in ER studies published after 2020 [40,49,50].

The Contribution of COVID-19 to Research Expansion

The year 2020 is an important year for this technology:

- Technological advancements led to the production of new ER tools since 2020 [40,49,50].
- FDA approval initiatives for VR (and AR) tools as Medical Devices, started in 2015, have gradually accelerated from 2020 (until 2022) [7] (see also: Table 2, based on an Excel dump from the public register; and the graphical presentation in Figures 2 and 3) with 63% of approval in the years 2020–2022.
- The COVID-19 Pandemic's momentum since 2020 has acted as a catalyst for numerous innovative technologies in the medical field.

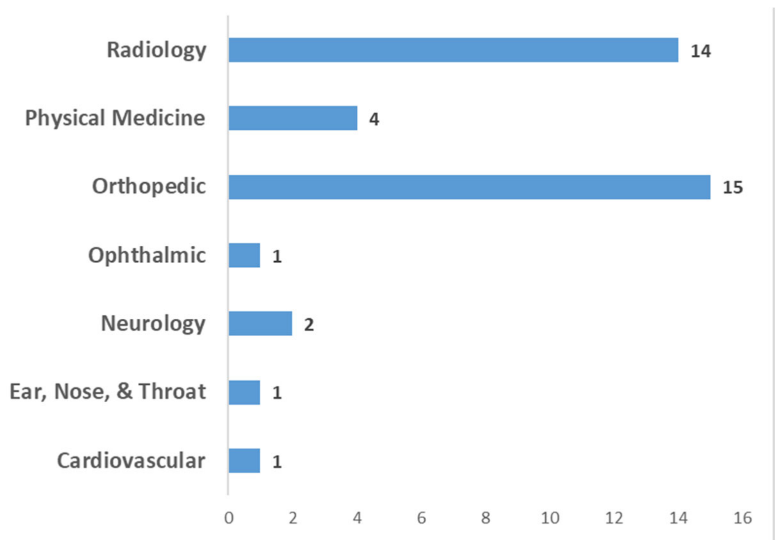

Figure 2. Categorization of the VR/AR medical devices approved by the FDA as extracted from the Excel available online.

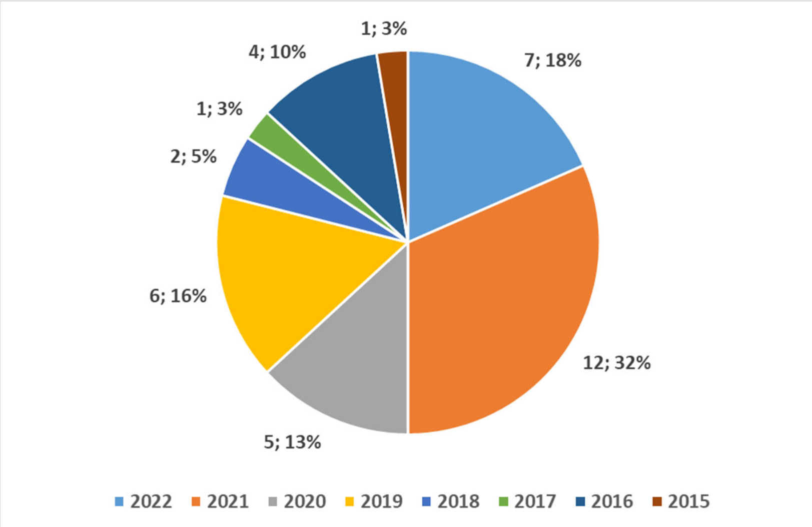

Figure 3. Distribution by year of FDA approbation of the VR/AR medical devices as extracted from the Excel available online.

Table 2. Dump from the FDA public excel related to the online register of the approved VR/AR medical device.

Date of Final Decision	Submission Number	Device	Company	Panel (Lead)
09/29/2022	K213034	SpineAR SNAP	Surgical Theater, Inc.	Orthopedic
09/01/2022	K220104	Knee+	Pixee Medical	Orthopedic
07/29/2022	K220733	OptiVu ROSA MxR	Orthosoft, Inc. (d/b/a Zimmer CAS)	Orthopedic
06/15/2022	K213684	SurgiCase Viewer	Materialise NV	Radiology
05/27/2022	K220146	VisAR	Novarad Corporation	Orthopedic
03/10/2022	K213751	NextAR TKA Platform My Knee PPS	Medacta International S.A.	Orthopedic
01/14/2022	K211254	ARAI Surgical Navigation System	Surgalign Spine Technologies	Orthopedic
11/16/2021	DEN210014	EaseVRx	AppliedVR, Inc.	Physical Medicine
11/10/2021	K210344	inVisionOS	PrecisionOS Technology Inc.	Radiology
11/05/2021	K210859	NextAR Spine Platform	Medacta International, SA	Orthopedic
10/20/2021	DEN210005	Luminopia One	Luminopia, Inc.	Ophthalmic
10/02/2021	K202927	EYE-SYNC	SyncThink, Inc.	Neurology
09/29/2021	K210726	Immersive Touch	ImmersiveTouch Inc.	Radiology
07/19/2021	K211188	xvision Spine system (XVS)	Augmedics Ltd.	Orthopedic
07/14/2021	K203115	ARVIS Surgical Navigation System	Insight Medical Systems Inc.	Orthopedic
05/14/2021	K210072	HOLOSCOPE-i	Real View Imaging Ltd.	Radiology
05/12/2021	K210153	NextAR RSA Platform	Medacta International SA	Orthopedic
04/21/2021	K202750	Knee+	Pixee Medical	Orthopedic
01/28/2021	K200384	HipXpert 3D Display and Anchoring Application	Surgical Planning Associates, Inc.	Orthopedic

Table 2. *Cont.*

Date of Final Decision	Submission Number	Device	Company	Panel (Lead)
10/27/2020	K202152	NextAR TKA Platform	Medacta International SA	Orthopedic
09/18/2020	K192890	SentEP	SentiAR, Inc.	Cardiovascular
07/17/2020	K201465	SuRgical Planner (SRP) BrainStorm	Surgical Theater, Inc.	Radiology
07/10/2020	K193559	NextAR TKA Platform	Medacta Inernational SA	Orthopedic
01/23/2020	K191014	Elements Viewer	Brainlab AG	Radiology
12/20/2019	K190929	xvision Spine system (XVS)	Augmedics Ltd.	Orthopedic
11/29/2019	K192186	I-Portal Neuro Otologic Test Center, I-Portal Video Nystagmo	Neurolign USA LLC	Ear, Nose, & Throat
08/29/2019	K183489	D2P	3D Systems, Inc.	Radiology
05/13/2019	K190764	SurgicalAR	MEDIVIS, Inc.	Radiology
03/18/2019	K183296	REAL Immersive System	Penumbra, Inc.	Physical Medicine
02/22/2019	K182643	IRIS 1.0 System	Intuitive Surgical	Radiology
09/21/2018	K172418	OpenSight	Novarad Corporation	Radiology
02/12/2018	K170793	SuRgical Planner (SRP)	Surgical Theater, LLC	Radiology
04/24/2017	K162748	MindMotionPRO	MindMaze SA	Physical Medicine
06/28/2016	K160584	Surgical Navigation Advanced Platform (SNAP)	SURGICAL THEATER, LLC	Radiology
02/12/2016	K153004	Clear Guide SCENERGY	CLEAR GUIDE MEDICAL	Radiology
02/05/2016	K151955	YuGo System	BIOGAMING LTD.	Physical Medicine
01/29/2016	K152915	EYE-SYNC	SyncThink Inc.	Neurology
01/21/2015	K142107	ECHO TRUE 3D VIEWER	ECHO PIXEL INC.	Radiology

Specifically regarding VR, whether alone, integrated with AR, or as part of ER, there has been a notable increase in publications in this realm since 2020 [16]. These trends are echoed in a plethora of research [51–60]. For instance, Mehraeen et al. [51] (2023) conducted a systematic review on telemedicine technologies and applications during the COVID-19 pandemic, also highlighting the role of VR in radiology teleconsulting, while Hayre and Kilgour [52] (2021) examined the current and future use of Virtual Reality in diagnostic radiography education amidst the pandemic. Similarly, Oulefki et al. [53] (2022) proposed Virtual Reality visualization for computerized COVID-19 lesion segmentation and interpretation, whereas Yeung et al. [54] (2022) delved into the current technology and future applications of Virtual Reality applications. Additionally, Liu et al. [55] (2024) and Amara et al. [56] (2022) investigated the augmented reality visualization and quantification of COVID-19 infections in the lungs, and also the use of augmented reality to aid COVID-19 diagnosis based on CT-scan segmentation using deep learning, respectively. Benbelkacem et al. [57] applied VR for CT Image-Based Classification and Visualization.

These studies underscore the growing recognition and adoption of immersive technologies like virtual and augmented reality in radiology, a trend reinforced by Bhugaonkar et al. [58] (2022) and Tsai et al. [59] (2023), who explored the role of these components integrated into the health domain. Furthermore, Ong et al. [60] (2021) delved into the potential of ER for enhancing telehealth both during and beyond the COVID-19 pandemic.

Standardization of VR in the Health Domain with a Focus on Radiology

As Ford once said, “True progress is only made when the benefits of a new technology become accessible to all”. Regarding VR, tangible progress can be measured if it is truly integrated into the health domain and its applications and opportunities are assessed. The integration of a device into the health domain must necessarily undergo certification to comply with regulatory processes before being introduced to the market and utilized within the healthcare system. VR systems intended for medical use are considered medical devices and must adhere to relevant certification processes, which vary based on their intended use and risk class. Regulatory bodies, such as the FDA for the US market, the EU Commission for the European market, and Health Canada for the Canadian market (among others), provide their respective roadmaps.

The FDA has addressed this integration issue and launched a dedicated website, last modified in September 2023 [7], which not only lists a registry of FDA-approved medical devices with AR/VR (38 in total) in the US, but also offers an interactive system for scientific and communicative dissemination, monitoring, and roadmaps specific to these medical devices. The communicative dissemination is tailored with a dual focus and specific language, considering the involved stakeholders, and includes important infographics on VR/AR targeted specifically for patients [61] and professionals [62].

Further exploration in this area [63] highlights that among the 38 approved medical devices, 14 are dedicated to radiology, while 15 are for orthopedics (see also Table 2 and Figures 2 and 3). Four are for physical medicine, two are for neurology and ophthalmology, one is for cardiovascular, and one is for otolaryngology, while there is not a specific categorization for robotics. However, radiology not only falls among the 14 devices, but also contributes to orthopedics and other sectors as an imaging provider. Therefore, radiology plays a crucial role in this domain.

Regarding radiological devices based on VR, AR, or extended reality, these, along with the introduction of other technologies, have also impacted PACS as medical devices [64,65]. However, it has been clarified that, as of the date of the latest dissemination updates, presently, the use of VR/AR medical devices in this domain, FDA approvals are primarily limited to research and informational purposes, such as aiding patients in understanding informed consent procedures [64,65]. Initiatives with a particular focus on patients in provision of the diffusion of these technologies have also been undertaken by the FDA [66].

Shifting the focus to Europe, it is evident that the current legislation is governed by Regulation (EU) 2017/745 of the European Parliament and the Council dated 5 April 2017 [67]. According to this regulation, VR is considered software as a medical device [68]. Based on a recent study reported in [69]:

- The transition towards this European directive from the previous one [70] will conclude by May 2024 with adoption across all member states.
- A delay in adopting technological innovations such as VR is highlighted, along with an invitation for more concrete actions. According to the authors, it must be clearly understood how a VR software for medical application [71,72] differs from a general exergame [73], considering the various medical areas in which VR [74] can be applied.

A innovative stance compared to the FDA and the EU Commission, which appears to be lagging behind, is represented by Health Canada, which recently approved a class II medical device [75] with VR for clinical diagnosis (previously limited to class I risk in other countries and never for direct diagnosis).

This innovative stance taken by Health Canada marks a significant shift in the regulatory landscape with potentially far-reaching implications. This recent approval of a class II medical device incorporating VR for clinical diagnosis represents a notable departure from previous regulatory frameworks. Traditionally, medical devices utilizing VR technology have been categorized as class I devices, indicating lower risk and not direct diagnostic capabilities. However, Health Canada's decision to approve a class II device for clinical diagnosis signals a recognition of the evolving role and potential of VR technology in healthcare. This decision not only reflects Health Canada's willingness to embrace innovative technologies, but also underscores a growing acceptance of VR as a viable tool for clinical diagnosis and patient care. By granting approval for a class II device, Health Canada acknowledges the increasing sophistication and reliability of VR-based diagnostic tools, paving the way for their wider adoption and integration into medical practice.

Moreover, this move may prompt other regulatory agencies, including the FDA and the EU Commission, to reassess their classification criteria for VR medical devices. As VR technology continues to advance and demonstrate its efficacy in healthcare settings, there is a growing need for regulatory frameworks that accurately reflect its capabilities and potential risks. Health Canada's decision could catalyze discussions and initiatives aimed at updating existing regulations to better accommodate the evolving landscape of medical technology. Furthermore, the approval of a class II VR medical device for clinical diagnosis opens up new possibilities for healthcare providers and patients alike. Overall, Health Canada's forward-thinking approach to regulating VR medical devices signals a promising future for the integration of Virtual Reality technology in healthcare.

1.3. The Rationale for a Narrative Review Study in This Field

Reviews are valuable for examining emerging and established themes in an emerging filed. Simultaneously, this analysis can also reveal less-explored and less-appealing topics. An overview of reviews, which analyzes a set of systematic reviews, provides a comprehensive view of these themes. Two possible approaches are to use a methodology for systematic reviews [76] or to rely on a narrative review methodology [77]. Narrative review is preferable when exploring a topic flexibly, obtaining a general overview without following a rigorous systematic methodology. It is suitable when aiming to develop conceptual or theoretical frameworks, prioritizing methodological flexibility over an objective synthesis of specific evidence, and when seeking a comprehensive overview. In terms of emerging topics and a low number of published studies, a systematic review might not be the most suitable choice due to its restrictive study selection, as we have verified through preliminary simulations before proceeding. And for this reason, we have chosen to undertake a narrative review examination of reviews. This strategic approach is aimed at delving deeply into the multifaceted themes within this domain, utilizing a flexible and less rigid analytical tool. This method allows us not only to gain a broad overview, but also to capture the intricate nuances associated with emerging themes, thereby enhancing our understanding of the subject matter. *The concept of VR within the field of radiology has undergone significant evolution, intertwining with advancements in technology while unlocking new potentials and diverse applications; ancient conceptions and new interpretations have succeeded each other, coexisting harmoniously*. The emerging questions motivating the overview are the following:

1. *What do scholars mean by Virtual Reality in radiology applications, and how do they perceive it?*
2. *How has the integration of Virtual Reality in radiology evolved over time, and what significant advancements and challenges have shaped this intersection, and what are the emerging themes/patterns?*
3. *How has virtual reality been integrated in the radiology domain with other innovative technologies (e.g., robotics, Artificial Intelligence, and Augmented Reality)?*
4. *In what ways has Virtual Reality demonstrated its potential to enhance diagnostic capabilities, improve medical training, or transform patient care within the field of radiology, and what are the current obstacles to overcome?*

1.4. Purpose of the Study

This study conducts a comprehensive narrative review that explores and synthesizes the existing literature on the intersection between virtual reality and radiology. This review aims to elucidate the evolution of this integration, critically analyze the advancements and challenges encountered, and provide a nuanced understanding of how virtual reality is influencing diagnostic practices, medical training, and patient care within the radiological domain. The overarching purpose is to offer valuable insights for clinicians, researchers, and healthcare stakeholders, fostering a deeper appreciation of the current state, potential applications, and future directions in this rapidly evolving field.

2. Materials and Methods

This narrative review used the ANDJ standardized checklist (reported in the Supplementary Material as Table S1) designed for narrative reviews [78]. Such a narrative checklist is a methodological tool that provides detailed and structured guidance during the review process. It aids in standardizing the review process by establishing key criteria for use during the analysis, making the process of constructing the study transparent.

The PubMed and Scopus databases were inserted in the overview. A qualification methodology was used to choose the studies, based on the assessment of qualified parameters [79]. Based on the cited study [79], we evaluated each contribution based on six key parameters:

1. *Clarity of study rationale in the Introduction.*
2. *Appropriateness of work's design.*
3. *Clarity in describing methods.*
4. *Clear presentation of results.*
5. *Justification and alignment of conclusions with results.*
6. *Adequate disclosure of conflicts of interest by authors.*

The scoring system involves assigning graded scores (1 = min; 5 = max) to each one of the first five parameters based on the quality of each criterion.

For the last parameter, a binary assessment (Yes/No) is made regarding the disclosure of conflicts.

To preselect studies:

- Each of the first five parameters must obtain a minimum score of 3.
- The last parameter must be marked as "Yes" for conflict disclosure.

Only peer-reviewed studies were included, including studies published at a congress that were accepted and published following a peer-review process.

The defined search query for the core of this study (narrative review of reviews) was the following: =

("*(virtual reality[Title/Abstract]) AND (radiology[Title/Abstract])*")

The procedure-based overview identified 20 studies review studies (among them being 3 systematic reviews), matching the 95.2% of the PubMed query [80].

These studies are as follows [81–100].

In the review work, in formulating introductory hypotheses, in supplementing the discussion, and as additional checks for controlling the core overview, we used also other keywords in different logic combination such as: "image", "imaging", "VR", "radiography", "image diagnostics", "VR"; other MESH terms, such as "Radiology", "Interventional Diagnostic Imaging", "Image Interpretation", "Computer-Assisted Radiographic Image Interpretation", "Computer-Assisted Tomography", "X-ray Computed Magnetic Resonance Imaging", "Ultrasonography Three-Dimensional Imaging", "Computer Simulation", and "User-Computer Interface"; and other correlated terms such as "Virtual reality simulation", "3D visualization", "Augmented reality radiology", "Virtual reality training", "Virtual reality applications in radiology", "Immersive technology in radiology", "Virtual reality software", "Medical virtual reality", and "Virtual reality in medical education".

Furthermore, targeted searches were also conducted on the official websites of certain international regulatory bodies in the healthcare field. This approach aimed to gather specific and authoritative information related to healthcare regulations from reputable sources. By exploring the content provided by these institutions, this review sought to ensure accuracy and relevance in addressing regulatory aspects within the healthcare domain.

3. Results

Below is an analysis of the trends of the studies in this field reported in Section 3.1, and a detailed analysis of the key elements emerging from the overview of each study (Section 3.2).

3.1. The Trends in the Studies on Virtual Reality in the Field of Radiology

A search was conducted on the PubMed database with search criteria outlined in Box 1, and yielded a total of 108 studies on the application of Virtual Reality in Radiology since the 1990s.

Box 1. The proposed composite keys.

(virtual reality[Title/Abstract]) AND (radiology[Title/Abstract])
(Virtual Reality[Title/Abstract]) AND (Radiology[Title/Abstract]) AND (applications[Title/Abstract])
(virtual reality[Title/Abstract]) AND (radiology[Title/Abstract]) AND (robotics)

Figure 4 illustrates the increase in the number of articles indexed in PubMed on the use of VR in radiology since the late 1990s, based on the search parameters given in Box 1. Figure 5 delineates the distribution of article types, specifically highlighting the prevalence of reviews (n = 18) and systematic reviews (n = 3) concerning the application of VR in radiology.

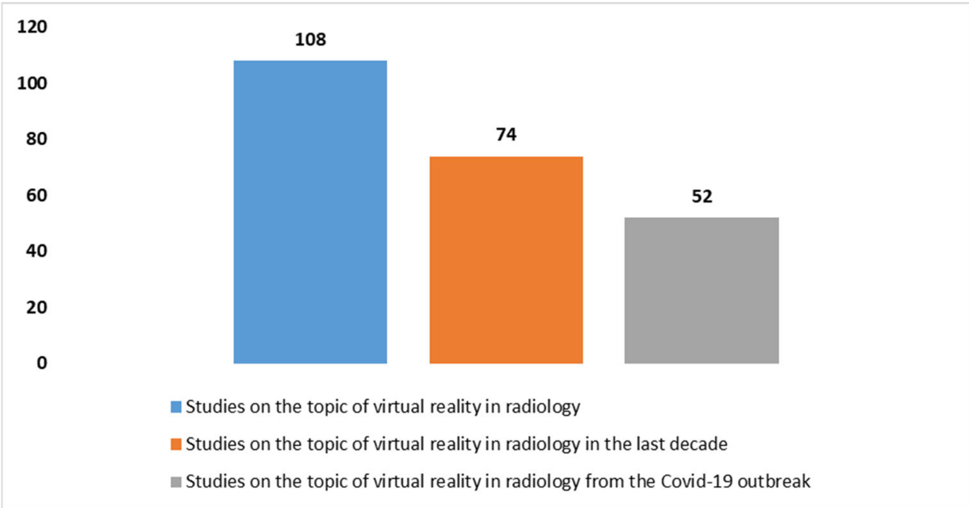

Figure 4. Studies focusing on Virtual Reality and Radiology.

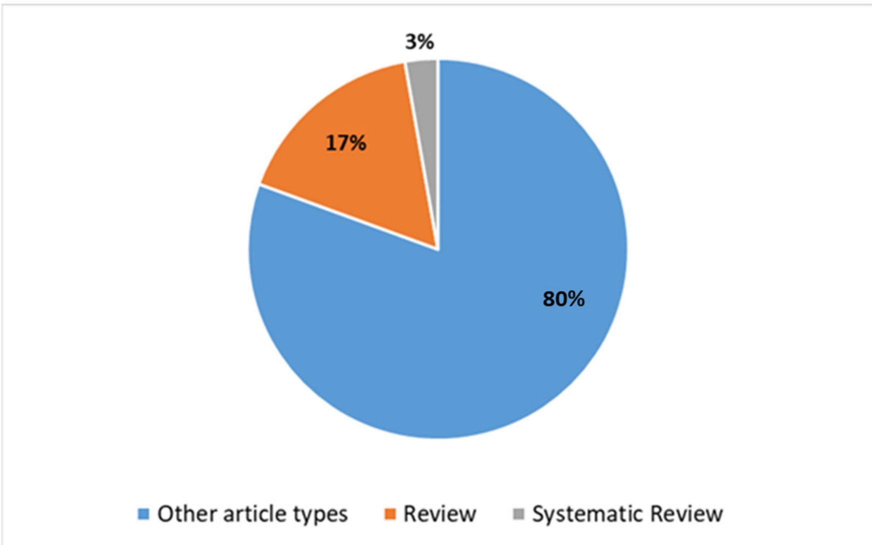

Figure 5. Article types focusing on Virtual Reality and Radiology.

Research on this topic has accelerated considerably in two important periods, as shown in Figure 6. The first major increase occurred in the last decade (from 2014 to the present), when 72.2% of all indexed articles on this topic were published in the PubMed database. This era was a defining moment that highlighted the growing interest and concerted efforts to improve knowledge and understanding of the application of VR in the field of radiology.

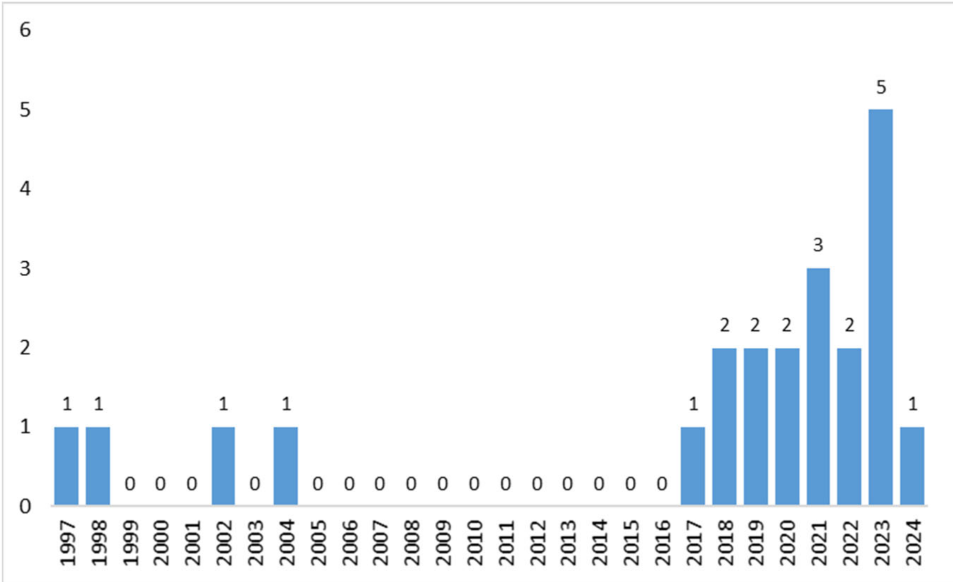

Figure 6. Temporal trend of reviews and systematic reviews published on the PubMed database from the 1990s to date.

After this initial upswing, a phase of even greater acceleration began with the outbreak of the COVID-19 pandemic. From 2020, almost half of all articles were published on this topic (48.1%). This increase can be attributed, as discussed in the Introduction, to the combination of three factors: Firstly, since 2020, there have been significant technological advancements leading to the development of new ER tools. Secondly, the FDA approval initiatives for VR and AR tools as medical devices, which began in 2015, saw a notable acceleration from 2020 to 2022. Approximately 63% of approvals occurred during this period. Thirdly, the COVID-19 Pandemic, starting in 2020, spurred the adoption of various innovative technologies in the medical field. The pandemic has been a key turning point for the adoption of technology in radiology, and has accelerated the digital transformation in various radiological settings.

In summary, the increase in PubMed articles on VR in radiology reflects the convergence of technological advances, the recognition of VR's potential to transform medical imaging and education, and the collaborative spirit of modern scientific research. Taken together, these elements underline the increasing importance of VR in improving radiological practice and patient care.

3.2. Key Findings: Common Emerging Message and Emerging Themes/Patterns

3.2.1. Common Emerging Message

The collective findings from the literature reviews suggest a potential profound transformation in the landscape of radiology, driven by advanced technologies such as VR, often integrated with AR, Artificial Intelligence (AI), and, in some cases, with 3D printing. These reviews consistently underscore the multifaceted directions of development of these technologies in the health domain, where digital radiology plays an undeniable role as a connector. One prevalent theme is the considerable potential of VR and AR in radiological education. The immersive nature of these technologies proves effective in enhancing learning experiences, particularly in radiology and anatomy education based on radiological images as sources [86]. The reviews stress their role in improving anatomy knowledge, providing realistic simulations and offering interactive environments for training purposes thanks to the digital radiology sources [83,95]. This educational transformation extends to dentistry, where VR integrated with digital radiology, as well as AI, AR, and 3D printing, are identified as interesting directions for supporting diagnosis, surgery, and patient care [96]. The synergy among VR and other technologies, such as AI, emerges as a key player in radiology, promising significant future improvements in diagnostic precision and treatment customization, and in minimally invasive treatments [88]. Despite the promises, the reviews, including von Ende et al. [84], acknowledge the existing obstacles limiting the widespread clinical acceptance of these solutions, emphasizing the need to overcome these challenges for broader adoption in interventional radiology. Simulation-based medical education (SBME) using VR stands out as a pragmatic solution for training radiology professionals. Reviews by Dankelman et al. [89] and Rooney et al. [99] emphasize the effectiveness and realism offered by VR in providing cost-effective and realistic training environments. Challenges in traditional training methods are addressed by proposing thoughtful development approaches based on models like Rasmussen's [89]. However, amidst the enthusiasm for technological advancements, the reviews consistently bring attention to challenges and the necessity for further research. The standardization of VR integrated with AR, usability concerns, and technical considerations are recurrent topics [83,85]. The need for specialized user interfaces designed for radiologists is highlighted to ensure better acceptance and meet professional requirements [87]. Each review [81–100] calls for caution and tempers enthusiasm, bringing us back to the real state of integration that currently allows for limited routine use. Gamba et al. [85] and Zhao et al. [94] extensively emphasize the call for additional research to comprehensively understand the benefits and address the barriers to adoption.

Overall, these literature reviews collectively paint a picture of a potential dynamic shift in the radiological landscape, driven by the integration of VR with other technologies. However, while celebrating the potential in this field for enhanced education, diagnosis, and patient care, the reviews advocate caution, emphasizing the importance of addressing challenges, standardizing practices, and conducting further research to fully realize the transformative potential of these technologies in the radiology domain [81–100]. Practically all studies also highlight the current limits with caution regarding ethical and legal aspects. In discussing the limitations and ethical considerations surrounding VR and AR in medical contexts, several key points emerge. An excellent synthesis of the collective message of caution can be found in [82]:

- *Firstly*, the phenomenon of "cyber sickness" is a notable concern. This refers to discomfort experienced by users, including symptoms like nausea and dizziness, which can occur when using VR and AR applications. The underlying cause is often attributed to a mismatch between the visual perception of motion and the input from the vestibular system. To mitigate this, developers are exploring various strategies such as synchronizing movement with the user's head motion and improving tracking accuracy.
- *Secondly*, in the realm of the VR and AR, ensuring accurate localization of virtual reconstructions over real-world anatomy is essential during image-guided procedures. Challenges include overcoming respiratory motion and organ deformation while maintaining smooth and accurate image movement. Moreover, the AR device must seamlessly integrate with the operator's senses and be lightweight and comfortable for prolonged use.
- *Furthermore*, while VR and AR have the potential to simulate reality, achieving high levels of realism requires substantial resources and expertise. Hence, prioritizing simpler simulations for tasks like training may offer more immediate value.
- Caution is warranted in the adoption of VR and AR technologies in radiology and generally in the health domain. Regulatory approvals aside, rigorous research is needed to ascertain their efficacy in improving medical workflows and patient outcomes. Additionally, ethical concerns arise regarding the potential for inaccurate

simulations to impact training quality and patient care. Collaborative oversight involving medical professionals, developers, and regulatory bodies is essential to ensure responsible integration.

Overall, addressing the limitations and ethical considerations of VR and AR technology is paramount for their safe and effective implementation in medical practice. Through careful research, strategic development, and collaborative oversight, these technologies can fulfill their potential to enhance healthcare delivery while safeguarding patient well-being.

3.2.2. Emerging Themes/Patterns

When analyzed in more detail, we can identify certain areas of common interest that were identified when examining the included studies.

- *Integration of VR and AR in radiology* Several reviews (Sutherland et al. [81], Elsayed et al. [82], Gamba et al. [85]) highlight the growth of VR and AR in radiology, emphasizing their potential to transform, in future, the clinical practice, medical education, and radiological workflows.
- *Integration of VR with AI and impact on Radiology* von Ende et al. [84], Gurgitano et al. [88], and Patel et al. [91] discuss the increasing role of AI in radiology, focusing on its applications in diagnostic radiology, interventional radiology, and its potential impact on patient care, education, and treatment planning.
- *Educational Applications of VR integrated with AR in radiology* Gelmini et al. [83], Chytas et al. [86], and McBain et al. [95] explore the effectiveness of VR and AR in medical education, particularly in radiology and anatomy, based on digital radiology imaging. The positive reception and effectiveness of these technologies in enhancing learning and skills acquisition are highlighted.
- *User Interface (UI) Evolution with VR in Radiology* Iannessi et al. [97] delve into the evolution of user interfaces in radiology, emphasizing the need for radiologist-specific UIs for better acceptance and usability. The study discusses alternatives such as touchscreens, kinetic sensors, and augmented/virtual reality for two- and three-dimensional imaging.
- *SBME and Training with VR in radiology* Reviews by Rooney et al. [99], Dankelman et al. [89], and Alvarez-Lopez et al. [100] focus on the importance of SBME and training, especially in radiation oncology, interventional radiology, and surgery. The effectiveness of VR and other technologies in providing realistic and cost-effective training solutions is highlighted.
- *Advances in Imaging Technology and VR in radiology* Ravindran [92], Dammann [97], ter Haar Romeny et al. [98], and Zhao et al. [94] discuss technological advances of VR integration with the digital radiology. The reviews emphasize improvements in image quality, 3D visualization, and the application of novel technologies, such as the 3D printing [92], both in diagnostic and interventional radiology.
- *Application of VR integration into radiology in Advanced Technology integration in Dentistry* Singhal et al. [96] specifically highlight the potential impact of VR, AR, and 3D printing in dentistry based on digital radiology imaging, covering aspects such as diagnosis, surgery, and patient care.
- *Shift in radiology education and Personalized Learning* Guimarães et al. [93] discuss the evolving trends in medical education, emphasizing a shift towards integrating basic and clinical sciences using technologies like 3D modeling and digital imaging. The potential role of AI and VR in personalized learning processes is highlighted.
- *Integration of VR into Extended Reality (ER) in Diagnostic radiology Imaging* Kukla et al. [90] focus on the use of ER in diagnostic radiology imaging, emphasizing its positive impact on patient positioning, medical education, and reduction of anesthesia use.
- *VR and Advancements in Difficult Airway Management* Ravindran [92] outlines advancements in managing difficult airways, including both the role of the digital radiology and 3D printing, suggesting opportunities in this field.

These emerging themes/patterns collectively indicate the trend of the development towards. However, the reviews also strongly remarks the need for further research, standardization, and overcoming challenges for broader adoption of these technologies. Another key point and focus of the review, which centered on various aspects of the integration of radiology with VR, was to comprehend both the scholars' perception of this integration and to analyze other technologies involved specifically (AI, AR, ER, robotics, 3D printing). Many variables come into play here, ranging from the perception of the concept of VR (which, according to initial hypotheses, we found to be quite extensive) and other technologies, to the emphasis on radiology. In the Supplementary Material (s.2), excerpts from each study are also provided for those scholars who are interested.

3.2.3. The Focus on the Role of the Radiology and on the Virtual Reality in the Overviewed Studies

As observed in the initial hypotheses, radiology, besides its dedicated practice in this field, holds a transversal role across various medical sectors (such as surgery, anatomy, orthopedics, pathology, etc.), given its responsibility for preparing 3D data through established standards and sharing channels (DICOM, PACS, RIS). The integration of RIS/PACS, as inferred from the analysis, is often regarded by scholars in an all-encompassing manner for medical diagnostics (including, also, MRI, echographies, and other devices not based on radiography processes). Therefore, we chose to accentuate these two fundamental viewpoints and structure a more detailed presentation of the data with a specific focus on these aspects as well. Table 3 delineates the key elements/points emerging from the overview of reviews and systematic reviews, with a particular emphasis on the two specific aspects of radiology and VR integration, including other integrations.

Table 3. Key elements/points emerging on the overview of reviews and systematic reviews.

Review Study	Key Points	Focus on Radiology	Focus on VR Integration
Sutherland et al. *(2019) [81]*	This study explores VR (also integrated with AR) growth in the radiology field, addressing technology limitations and proposing a framework for medical image processing in VR/AR, suggesting its integration into radiological workflows and various clinical settings.	Discusses considerations for placing these methods directly into a radiology-based workflow and details on how it can be applied to a variety of clinical scenarios.	A comprehensive conceptual framework has been introduced to understand the various VR experiences also integrated with AR, categorized by technological sophistication. This framework assists in integrating VR technologies directly into radiology workflows, offering new perspectives on medical imaging interpretation and utilization.
Elsayed et al. *(2020) [82]*	This review provide an overview of VR (also integrated with AR) technologies, their current applications in radiology, future developments, and the challenges to their wider adoption in digital imaging.	Potential applications in diagnosis, surgical planning, interventional procedures, image interpretation, medical education, and 3D printing.	A comparison between 3D printing and VR/AR is reported. VR/AR offer interactive visual simulations with real-time render customizability, contrasting with the pre-printing limitations of 3D printing. While both require software, VR/AR systems are accessible via head-mounted displays (HMDs) without the need for a 3D printer or printing materials. Additionally, VR/AR typically have quicker turnaround times and varying ease of use, with potential side effects like cyber sickness, unlike 3D printing which lacks such effects.

Table 3. *Cont.*

Review Study	Key Points	Focus on Radiology	Focus on VR Integration
Gelmini et al. *(2021)* [83]	This systematic review compares VR simulations to traditional teaching in interventional radiology, analyzing five trials using the Kirkpatrick model with mixed outcomes. Findings suggest VR enhances learning effectively, yet underlines the need for standardized VR integration and further research in this field.	Assesses the efficacy of VR as an educational tool in interventional radiology, particularly in enhancing skill transfer and reducing medical errors. Studies indicate that VR-based teaching facilitates skill acquisition among residents and novice physicians, potentially shortening the learning curve and improving patient outcomes. Additionally, VR-based simulation training shows promise in reducing morbidity, mortality, and healthcare costs associated with interventional radiology procedures, although further research is needed to evaluate its effectiveness across different populations and procedures.	VR is used in interventional radiology education by providing immersive simulations of procedural techniques, allowing trainees to practice in a virtual environment before performing procedures on patients. This method enables learners to acquire skills safely and effectively, leading to reduced procedural times, fewer technical errors, and ultimately better patient outcomes.
von Ende et al. *(2023)* [84]	Focuses on VR's role in medicine, especially in diagnostic radiology, and points to its emerging potential in interventional radiology. The review discusses VR's promise in enhancing radiological diagnosis and treatment through AR, AI, and radio genomics, despite current obstacles limiting clinical acceptance. It emphasizes the need for overcoming challenges to foster AI's broader clinical adoption in interventional radiology.	The applications of VR integrated with AI and AR in interventional radiology is discussed. It spans across pre-procedural, intra-procedural, and post-procedural phases. Pre-procedural uses involve patient selection, radiogenomics, AR, and VR. Intra-procedural applications encompass procedural guidance and management of radiation exposure. Post-procedural applications focus on evaluating procedural outcomes and facilitating follow-up care.	The potential roles of VR, AR, and AI are discussed in the pre-procedural, intra-procedural applications, and post-procedural applications.
Gamba et al. *(2024)* [85]	This study explores the impact of VR also integrated with AR on digital imaging in radiology, highlighting the transformation of workspaces into interactive environments. Despite the infancy of research on VR-simulated radiology stations, the review stresses the need for further studies to understand their benefits and address adoption barriers, underscoring the technology's potential to innovate radiological practices.	The focus is on exploring the potential applications of VR and Augmented Reality technology, particularly in redesigning the traditional radiology workstation (reading room) to enhance diagnostic interpretation.	Specifically within radiology, VR technology, also integrated with AR, is being explored to redesign traditional workstations, such as reading rooms, to improve diagnostic interpretation. Despite its promising potential, further research is needed to understand the full scope of benefits and address barriers to adoption.
Chytas et al. *(2021)* [86]	This review examines the benefits of VR in radiology and anatomy education, showing, through seven studies, that VR is well received and effective in enhancing anatomy knowledge. The findings advocate for VR's integration in teaching, suggesting significant improvements in radiology education within anatomy courses.	The focus is on radiology in conjunction with anatomy education involving VR and AR. Studies have shown positive outcomes when radiology is taught alongside anatomy using VR and AR, with improvements observed in students' academic performance and perception of the educational intervention.	Integration of VR and AR into anatomy education alongside radiology holds promise for enhancing learning experiences, and may encourage educators to adopt such approaches. Different VR and AR solutions are discussed.

Table 3. *Cont.*

Review Study	Key Points	Focus on Radiology	Focus on VR Integration
Iannessi et al. *(2018)* [87]	This review navigates the evolution and future of UIs in radiology, noting the dominance of mouse and keyboard while evaluating alternatives like touchscreens and VR/AR for 2D and 3D imaging applications. The study stresses designing radiologist-specific UIs for better acceptance and usability, indicating a move towards UIs tailored to radiology's unique needs.	The focus on radiology is on improving user interfaces (UI) for radiologists, especially with the evolution of digitalization and the increasing use of teleradiology. Designing specific UI tailored to radiologists' needs, both in terms of hardware and software, is crucial for enhancing efficiency and productivity.	Advances in technology, such as touch technology and VR/AR, show promise in optimizing UI the design and facilitation of tasks like 3D image display and manipulation, particularly in interventional radiology units where contactless interfaces are preferred.
Gurgitano et al. *(2021)* [88]	This study explores AI's role in radiology since the 1950s, enhancing diagnostic precision and treatment through machine and deep learning. Highlighting AI's synergy with AR and VR in minimally invasive treatments, the study anticipates AI's broad impact on IR, from patient screening to education, signaling a future where AI substantially boosts radiology and patient care.	The focus is the diagnostic and interventional radiology and the potential of integration of VR, AI, and AR.	The potential opportunities of AR/VRA/AI to streamline workflows, improve diagnostic accuracy, and enhance procedural planning and execution are discussed.
Dankelman et al. *(2004)* [89]	This review explores VR's potential in interventional radiologist training, offering a realistic and cost-effective solution amidst the challenges of traditional and alternative methods, while advocating for further research and a thoughtful development approach based on Rasmussen's model.	The focus on radiology revolves around exploring the potential of VR in training interventional radiologists to address the increasing procedural complexity and the limitations of traditional training methods.	VR emerges as a promising solution offering a realistic and cost-effective training environment, although its effectiveness in interventional radiology (IR) training requires further research. The study proposes using Rasmussen's model of human behavior to evaluate VR training's potential for IR education and to guide the development of future training methods.
Kukla et al. *(2023)* [90]	This review describes the decade-long application of ER (including the VR) in diagnostic imaging in digital radiology, noting its benefits in patient positioning, medical education, and reducing anesthesia use, while calling for more research to address clinical integration challenges and fully realize ER's healthcare potential.	The focus in radiology is the medical education and diagnostic imaging.	Discusses specific applications such as the DIVA system for facial trauma diagnosis and the Magic Mirror system for projecting 3D anatomy images onto the body. Despite their potential benefits, challenges such as cost-effectiveness, standardization, and addressing cybersickness need to be addressed. Further research and standardization efforts are necessary to fully realize these benefits and ensure their effectiveness in clinical practice.
Patel et al. *(2020)* [91]	This review explores the transition to virtual interviews in residency programs due to COVID-19, discussing challenges, opportunities, and strategies for effective presentation and assessment, emphasizing preparation, technology, and adaptation in the selection process.	The focus is on the transition to virtual readiness in the residency recruitment process, particularly in the field of radiology.	It emphasizes the importance of preparing both applicants and programs for virtual interviews, updating online resources, and investing in online platforms for effective communication between applicants and program personnel. VR is recalled as a potential technology with which people are becoming familiar.

Table 3. *Cont.*

Review Study	Key Points	Focus on Radiology	Focus on VR Integration
Ravindran (2023) [92]	This study emphasizes radiological advances like ultrasound, MRI, CT scans, and virtual endoscopy in managing difficult airways, noting their role in improving clinical standards and patient safety through enhanced diagnostics and training.	The focus is on advancements and innovations in managing the difficult airway within the field of radiology. It discusses various diagnostic techniques such as airway and neck Ultrasonography, MRI, and CT.	Discusses predictive tools like Virtual Endoscopy (VE) and 3D printing are discussed. Additionally, the study explores developments in airway devices, adjuncts, guidelines from organizations like the Difficult Airway Society and the American Society of Anesthesiologists, and emerging technologies such as VR for training and patient counsel.
Guimarães et al. *(2017) [93]*	This review discusses the shift in medical education in radiology towards integrating basic and clinical sciences with new technologies like 3D modelling and digital imaging, highlighting the future role of AI and VR in personalizing learning, essential for addressing medical education's complexity.	In the context of medical education and anatomy education specifically, radiology plays a crucial role in providing complementary imaging modalities for studying anatomy. Traditional methods like cadaveric dissection are being supplemented or even replaced by newer technologies such as radiological imaging (e.g., X-rays, CT scans, and MRI scans). These imaging techniques offer detailed visualizations of anatomical structures in living organisms without the need for invasive procedures.	In the context of VR in Medical Education and Anatomy Education, the focus lies on enhancing the learning experience through immersive and interactive simulations of anatomical structures. VR technology allows students to explore the human body in three dimensions, providing a highly realistic and engaging learning environment. With VR, students can visualize complex anatomical structures from various angles and perspectives, offering a deeper understanding of spatial relationships and anatomical details. They can interact with virtual models, manipulate anatomical components, and simulate procedures in a risk-free setting.
Zhao et al. *(2023) [94]*	This study explore the shift in IR training to using anatomical phantom models made possible by material technology advances, highlighting gel-based and 3D printing methods' role in this safer cost-effective alternative, amid current challenges and future research directions.	The focus is on the development of anatomical phantoms for medical training, particularly in the field of interventional radiology.	Researchers and physicians explore methods such as gel-based and 3D printing-based approaches to create these phantoms, aiming to provide safe and efficient training alternatives to traditional methods on real patients. Despite advancements, challenges such as time-consuming processes and the need for low-cost materials that accurately simulate tissues and organs remain to be addressed for widespread application.
McBain et al. *(2022) [95]*	This scoping review focused on anatomical education across training levels, and evaluated its modalities, urging further research on AR's effects on skills, cognitive load, and performance with robust designs and validated tools.	The review aims to identify different AR applications specifically within the context of radiology education, highlighting the role of AR technology in improving the understanding and visualization of anatomical structures relevant to radiological practice.	The focus of this review is on identifying and evaluating different augmented reality modalities used in teaching anatomy to students, health professional trainees, and surgeons. It examines the assessment tools utilized to evaluate the performance of these AR modalities, highlighting variables such as usability, feasibility, acceptability, visuospatial ability, cognitive load, time on tasks, and academic achievement outcomes for further exploration and understanding of AR's role in anatomical education.
Singhal et al. *(2023) [96]*	This literature review highlights how the technological advances like AI, VR, AR, and 3D printing have the potential to contribute to dentistry across diagnosis, surgery, and patient care, using radiology images, underscoring the need to understand their benefits and limitations for successful integration.	The focus is on oral radiology, a specialized field of dentistry dedicated to diagnosing and treating oral diseases using various imaging methods. The primary objective of oral radiology is to identify pathologies such as cysts, tumors, and infections in the oral cavity. The study also highlights the wide array of imaging techniques employed in oral radiology, including radiographs, CT scans, MRI, PET scans, and ultrasound, each serving specific diagnostic purposes related to dental and oral health.	The focus is on the integration of VR AR and MR technologies in oral surgery. The study highlights the potential benefits such as providing detailed anatomical information, facilitating surgical planning, enhancing dental anesthesia administration training, and assisting in various oral and maxillofacial surgeries. Additionally, the study highlights the potential of the AI integration in oral surgery, particularly in interpreting diagnostic imaging and optimizing treatment planning for conditions like impacted third molars and orofacial deformities.

Table 3. *Cont.*

Review Study	Key Points	Focus on Radiology	Focus on VR Integration
Dammann (2002) *[97]*	Focusing on significant progress in radiology image processing, this study highlighted improvements in image quality, 3D visualization, and automated clinical applications like treatment planning and intervention guidance. It emphasizes the growing necessity for specialized skills in image handling and suggests evolving roles within radiology specialties due to these technological advances.	The focus is on the potential advancements in medical imaging processing and analysis methods in radiology, based on various techniques such as preprocessing algorithms, three-dimensional visualization, registration, segmentation, and automated quantification analysis.	The focus on VR in this piece is primarily on its integration into various aspects of medical imaging processing and analysis. VR technologies are highlighted as part of three-dimensional visualization techniques, such as volume rendering and virtual endoscopy, to evaluate sectional imaging data sets. Additionally, VR is mentioned in the context of three-dimensional therapy planning, simulation, and intervention guidance, alongside other technologies like medical modeling, surgical robots, and navigation systems. The article emphasizes the increasing use of VR in clinical applications and underscores the need for specialized skills in utilizing VR for the production and postprocessing of radiological imaging data. These methods have practical implications for radiologists in their daily work, and pave the way for future developments in medical imaging technology and its applications.
Romeny et al. *(1998)* *[98]*	This review describes advancements in diagnostic 3D radiology, emphasizing the impact of 3D rendering software and computer vision on improving imaging and anatomy visualization through processes like segmentation and ray casting. The paper highlights the role of modern workstations in facilitating the integration of multimodal data and interactive 3D image processing, significantly benefiting radiology practices and anatomical training.	The focus of this study in radiology is on the impact of computer-assisted techniques in various aspects of diagnostic radiology. It highlights the essential tasks in radiology, such as providing patient management information, navigation for minimally invasive therapy and surgery, and assessing effectiveness. The study discusses how computers aid in these tasks, particularly through advanced visualization techniques like 3D volume rendering and surface rendering, which allow for a better understanding of complex anatomical structures. Additionally, computer-assisted techniques are crucial in tasks like multiplanar reformatting, maximum intensity projection of CT and MRI angiography, and comparisons of different functional imaging modalities. Furthermore, the study delves into the challenges faced in radiology, such as noise reduction in images, and discusses advanced techniques like nonlinear diffusion filtering to address these challenges effectively. It also explores the importance of accurate registration of multiple imaging modalities for integrated visualization and analysis. Overall, the study emphasizes the significant role of computer-assisted techniques in enhancing various aspects of diagnostic radiology, from image processing and analysis to treatment planning and intervention guidance.	While the study primarily focuses on computer-assisted techniques in diagnostic radiology, it does not extensively discuss VR specifically. However, it does mention the use of modern workstations in operating rooms for guidance and even robotic assistance, which can potentially involve VR technologies. Additionally, it briefly touches upon the concept of interactive volume visualization, which aligns with some aspects of VR where users can manipulate datasets in real-time for optimal understanding and exploration.

Table 3. *Cont.*

Review Study	Key Points	Focus on Radiology	Focus on VR Integration
Rooney et al. *(2018)* [99]	This systematic review evaluates SBME in radiation oncology, demonstrating its effectiveness in enhancing competencies like clinical decision-making and treatment planning through 54 studies. They advocate for SBME's integration into training programs, noting the need for better reporting standards and centralized resource utilization for broader adoption.	This study focuses on SBME in radiation oncology. The study emphasizes the need to recognize SBME as a valuable component of radiation oncology education and advocates for its diversification beyond contouring skills. It suggests including a broader range of skill sets and targeting a wider variety of learners, including non-physician members of the oncology team. Ultimately, the study underscores the importance of establishing a framework for SBME in radiation oncology education to ensure its widespread acceptance and integration into training methodologies.	The study provides an overview of SBME interventions used in radiation oncology education. Among the SBME interventions identified, VR/haptic systems were mentioned, accounting for 13% of the total interventions. This indicates that VR technology is being utilized to some extent in radiation oncology education, alongside other simulation-based approaches. While the study does not delve into details about the use of VR specifically, it suggests that SBME interventions, including those utilizing VR, have shown effectiveness in teaching various radiation oncology competencies. It also hints at the potential for VR to be employed in teaching procedural skills, such as brachytherapy, and in simulating patient encounters to enhance communication and support skills.
Alvarez-Lopez et al. *(2019)* [100]	This systematic literature review analyses the application of devices like Microsoft Kinect and Leap Motion Controller in radiology and surgery for gesture-based image manipulation, showing promise for affordable, portable simulators in minimally invasive surgery training. This study indicates these technologies could transform raining and preparation, although their application in sterile surgical environments remains under-explored.	The study primarily focuses on the use and integration into radiology of commercial off-the-shelf (COTS) devices, such as the Microsoft Kinect (MK), the Leap Motion Controller (LMC), and the Myo armband, in various medical applications, particularly in surgery, robotic surgery, and training simulations. The fields of applications are the following: Application in Surgery; Application in Robotic Surgery; and Application in Training and Simulation.	COTS devices, particularly, motion-sensing technologies like the MK and the Leap Motion Controller LMC, in medical settings, specifically surgery and training have been investigated. These devices enable contactless interaction with medical images and data in environments such as operating rooms, addressing the need for real-time manipulation of medical images without compromising sterility protocols. Key points highlighted in the text include: Evaluation of Individual Devices: The study discusses the performance and characteristics of MK and LMC, both of which use infrared cameras. It compares their features, such as accuracy, interaction range, and device dimensions. Advantages and Limitations: It outlines the advantages of these devices, such as their low cost, portability, ease of use, and high gesture recognition rates. However, it also identifies limitations, such as latency issues, limited gesture recognition, and interference in small environments for MK, and performance alterations due to environmental factors and occlusion phenomena for LMC. Application in Robotic Surgery: The study discusses the application of gesture-based COTS devices in robot-assisted surgery, highlighting challenges related to cost, accuracy, and robustness. While some studies suggest potential applications for workflow monitoring and training purposes, others indicate limitations in controlling surgical robots using these devices. Training and Simulation: It explores the use of COTS devices in surgical education and simulation, particularly in teaching anatomy, bronchoscopy, colonoscopy, and minimally invasive surgery skills. The study discusses the development of VR simulators based on these devices and their potential in training for robotic surgery.

4. Discussion

The discussion is organized into five parts. The first part, editorially translated in Section 4.1, presents the interpretation of the results, highlights opportunities, and suggests directions for further investigation. The second part, editorially translated in Section 4.2, complements the analysis with insights into areas where studies have focused on less, particularly in robotics. Section 4.3 reports a synoptic diagram linked with the study. The fourth and fifth parts, in Sections 4.4 and 4.5, respectively, consist of the takeaway message and the limitations of the study.

4.1. Interpretation of Results of the Narrative Review, Opportunities, Limitations, and Suggestions for a Broader Investigation

The historical trajectory of VR applications in radiology, dating back to 1994 [16], is outlining various areas of interest with the focus of the VR integration in radiology. In light of these considerations, we embarked on a comprehensive overview of reviews within this particular domain. The trends of dissemination, as illustrated in the results (Figure 6), have notably unveiled a rapid acceleration in scientific production in this field, particularly during the recent period characterized by the COVID-19 pandemic. Reviews play a pivotal role in pinpointing the stabilization of research themes and, indirectly, shed light on the topics that resonate most with scholars.

Upon a closer examination of the trajectory of scientific production in reviews (Figure 7), a discernible pattern emerges, showcasing a distinct shift following an initial surge of interest in this field. Intriguingly, there was a notable dip in the production of scientific reviews from 2005 to 2016. Further delving into the matter using the composite key provided in Box 1, position 2, it becomes evident that the overall trend in scientific production—encompassing not only reviews, but all applications—experienced a comparable plateau (Figure 7). This plateau is likely attributed to the challenge faced by scholars and stakeholders in perceiving and documenting a stable integration of developments within the health domain.

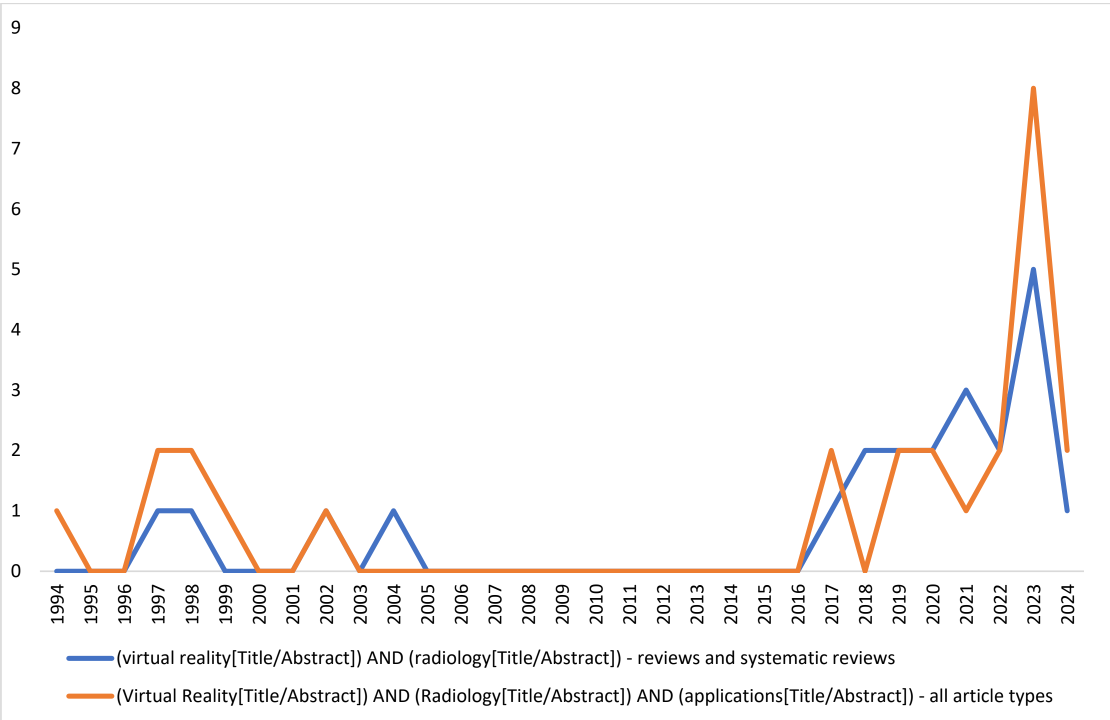

Figure 7. Comparative analysis of publication trends for virtual reality in radiology and their applications from the 1990s to date.

An exploration of this trend reveals a resurgence of interest from the year 2017 onwards. During this period, more affordable hardware and software have become increasingly widespread. Concurrently, regulatory initiatives within the medical device domain have been initiated. Notably, in Europe, Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices was enacted around this pivotal period, amending Directive 2001/83/EC, Regulation (EC) [101]. Innovative facets, such as recognizing software as a medical device, have played a crucial role in fostering the diffusion and rekindling of interest in this field starting from 2017, even if subsequent studies have brought to light a notable delay in the adaptation of member states to the directive, particularly regarding VR [69] the process of adjusting this regulation to accommodate ER systems has proven to be quite challenging. Simultaneously, regulatory bodies like the FDA have taken progressive steps by compiling and publishing lists of these devices based on VR and AR, a resource accessible online [7] (Table 2, Figures 2 and 3). Even though scientific paper writing is very rarely heavily influenced by regulatory initiatives, it could be interesting to delve deeper with targeted studies to explore if there is a correlation between the highlighted growth of interest and standardization activities.

All of this provides indirect additional motivation and justification for our review study. Our review has identified broad overarching themes and patterns that only partially cover the areas highlighted in [17] (discussed later in this paper).

Significant opportunities, along with limitations and areas requiring further investigation, have been identified from this overview.

4.1.1. Emerging Opportunities

The literature underscores a wealth of opportunities at the junction of VR and medical imaging in the field of radiology. VR simulations have proven remarkably effective in medical education, notably in radiology and anatomy teaching [86]. Their immersive nature enhances learning outcomes, emphasizing the need for standardized integration [83]. Moreover, VR holds significant promise in improving radiological diagnosis and treatment planning. By providing intuitive tools for three-dimensional visualization of complex anatomical structures and pathologies, VR applications aid radiologists in making more informed diagnostic decisions while reducing interpretation time [84]. In treatment planning, VR may offer support in preoperative assessment and intraoperative guidance [82]. Surgeons can simulate surgical procedures in virtual environments, exploring various approaches and anticipating challenges before surgery. During procedures, AR overlays real-time imaging data onto the surgeon's field of view, enhancing anatomical guidance and accuracy, thereby minimizing intraoperative complications.

Collaborative diagnostic workflows are also facilitated by VR platforms, allowing radiologists to remotely collaborate in real-time, regardless of geographical barriers [87]. Shared virtual workspaces enable experts to review cases together, exchange insights, and formulate optimal treatment strategies, thereby leveraging collective expertise and improving diagnostic consensus.

In medical education [82], VR provides immersive, simulation-based learning experiences. Students can practice surgical procedures, navigate complex anatomical structures, and engage in realistic clinical scenarios within a safe virtual environment. This hands-on approach fosters procedural skills, decision-making abilities, and teamwork dynamics, preparing learners for real-world clinical practice with confidence and competence.

The integration of VR into radiology workstations highlights the potential for interactive and dynamic environments, albeit with a call for more comprehensive research [85]. Tailored designs are necessary to meet radiologists' unique requirements, reflecting the evolving landscape of VR technology in medical imaging.

In conclusion, the convergence of VR and radiology signifies a transformative paradigm in radiological diagnosis, treatment planning, and medical education. VR's immersive capabilities offer unprecedented levels of precision, efficiency, and collaboration, revolutionizing the way healthcare professionals approach patient care and education.

These opportunities reflect a dynamic landscape, emphasizing *the potential for transformative advancements in healthcare*, *medical education*, *and diagnostic practices*. Table 4 outlines the emerging opportunities synthesized from the analysis, succinctly summarizing the key findings in alignment with the referenced studies reported in a column.

Table 4. Opportunities suggested by the overviewed studies.

Associated Studies	Opportunities	Description
Gelmini et al. *(2021) [83]* *Chytas* et al. *(2021) [86]*	*Enhanced Medical Education*	The integration of VR and AR offers unprecedented opportunities to enhance medical education. Realistic simulations and interactive environments improve learning experiences, particularly in radiology and anatomy education.
Gurgitano et al. *(2021) [88]*	*Improved Diagnostic Precision*	AI, in conjunction with technologies like AR and VR, has the potential to significantly improve diagnostic precision in radiology. This not only enhances accuracy, but also aids in personalized treatment planning.
Singhal et al. *(2023) [96]*	*Transformative Impact on Dentistry*	Advances in technologies such as AI, VR, AR, and 3D printing present opportunities for a substantial impact on dentistry. From diagnosis to surgery, these innovations promise improved patient care and shorter treatment times.
Dankelman et al. *(2004) [89]* *Rooney* et al. *(2018) [99]*	*SBME*	VR, particularly in the form of SBME, provides a realistic and cost-effective solution for training healthcare professionals. This opportunity addresses challenges in traditional training methods, offering immersive environments for skill acquisition.
Sutherland et al. *(2019) [81]* *von Ende* et al. *(2023) [84]*	*Technological Integration in Clinical Workflows*	The integration of VR and AR into clinical workflows, including diagnostic radiology and interventional procedures, presents opportunities for increased efficiency and accuracy in patient care.
Guimarães et al. *(2017) [93]*	*Personalized Learning in Medical Education*	The shift towards integrating basic and clinical sciences, supported by technologies like AI, VR, and learning analytics, opens opportunities for personalized learning processes in real time, addressing the complexity of medical education.
Ravindran (2023) [92]	*Application in Difficult Airway Management*	Technological advancements, including ultrasound, MRI, CT scans, virtual endoscopy, and 3D printing, offer opportunities to improve standards in difficult airway management. This includes enhanced diagnostics, training, and patient counseling.
Iannessi et al. *(2018) [87]*	*Evolution of User Interfaces*	The evolution of user interfaces, encompassing touchscreens, kinetic sensors, and augmented/virtual reality, presents opportunities for designing interfaces specifically tailored to radiologists. This addresses usability concerns and ensures better acceptance.
Kukla et al. *(2023) [90]*	*ER in Diagnostic Imaging*	ER, as explored in diagnostic imaging, offers opportunities to improve patient positioning, medical education, and potentially reduce the need for anesthesia. The interactive benefits of ER in anatomy and patient positioning are recognized.
Zhao et al. *(2023) [94]*	*Advancements in Surgical Training Models*	The development of anatomical phantom models using gel-based and 3D printing methods for surgical training in interventional radiology presents opportunities for safer, cost-effective alternatives. This allows for realistic simulations of multi-layer tissue structures.
Patel et al. *(2020) [91]*	*Shift to Virtual Interviews*	The shift to virtual interviews in residency programs due to the COVID-19 pandemic presents opportunities for optimizing interview processes, leveraging technology for effective presentation and assessment, and exploring new formats for interaction in the selection process.
Dammann (2002) [97] *ter Haar Romeny*et al. *(1998) [98]*	*Improvements in Image Processing*	Advancements in image processing, including pre-processing algorithms, 3D visualization, and segmentation methods, offer opportunities for automated quantification, treatment planning, and intervention guidance in radiology.
Alvarez-Lopez et al. *(2019) [100]*	*Application COTS Devices*	The application of COTS devices, such as Microsoft Kinect and Leap Motion Controller, in radiology and surgery for gesture-based image manipulation offers opportunities for affordable portable simulators in minimally invasive surgery training.

4.1.2. Emerging Limitations and Areas Needing Broader Investigation

The overview has also highlighted significant limitations. The quality limitations and technological constraints faced by VR and AR sometimes hinder their widespread adoption in clinical applications [81]. Constraints in integrating VR and AR in healthcare include hardware limitations, software development challenges, and concerns about data accuracy and privacy. High-quality VR experiences require powerful computing equipment and specialized headsets, while AR devices may have limitations in field of view and tracking accuracy. Developing medical-grade VR and AR applications involves collaboration among developers, healthcare professionals, and regulatory bodies to meet safety standards, which can be time-consuming. Ensuring the reliability and integrity of medical data in virtual environments is crucial for preventing misinterpretation, while safeguarding patient data from breaches is essential for maintaining trust and compliance. Despite these challenges, ongoing advancements in hardware technology, software development practices, and regulatory frameworks are gradually addressing the limitations of VR and AR in clinical applications. Collaborative efforts between industry stakeholders, research institutions, and healthcare organizations are driving innovation and paving the way for the wider adoption of VR and AR in improving patient care, medical training, and therapeutic interventions [84].

The potential benefits of VR-simulated radiology stations remain largely unexplored, with research being in its infancy. More studies are needed to understand the applications and overcome barriers to adoption [85]. Usability challenges persist in UIs for radiologists, with mouse and keyboard dominance. Tailoring UIs to the specific needs of radiologists is essential for better acceptance and integration [87].

VR training, while promising for the training of interventional radiologists, faces challenges related to costs and ethical considerations. Investigating cost-effectiveness and ethical implications is crucial for informed decision-making [89]. ER positive impact on diagnostic procedures is hindered by challenges in clinical integration. Further research is required to address the associated cost-effectiveness and integration challenges [90]. The shift to virtual interviews in residency programs introduces challenges in technology adaptation and effective assessment. Strategies need to be developed to overcome these challenges and ensure a smooth transition [91]. In the realm of difficult airway management, despite technological advances, challenges persist in widespread adoption. Attention needs to be directed towards guideline compliance and effective application in clinical settings [92]. The transition from traditional training to VR in surgery encounters hurdles such as ethical concerns and high costs. Future research and thoughtful development approaches are essential for effective integration [89].

While SBME is recognized for its effectiveness, improved reporting standards and centralized resource utilization are needed for broader adoption in radiation oncology training programs [99]. The application of COTS devices in surgery remains exploratory, especially in sterile environments. Further exploration is essential to understand their potential in contributing to training and preparation [100].

In discussions concerning the limitations and ethical considerations surrounding VR and AR in this field, several key points emerge, sometimes in a nuanced way, and in another one in a profound way, from the overviewed studies [81–100]. A comprehensive synthesis of the collective message of caution can be found in [82]. The integration of VR and AR in healthcare raises ethical and legal concerns, including “cyber sickness”, precise localization of virtual reconstructions, and device integration. Caution is advised, stressing the need for thorough research, collaborative oversight, and addressing ethical issues for responsible implementation [82].

Table 5 outlines the emerging limitations synthesized from the analysis, succinctly summarizing key findings in alignment with the referenced studies reported in a column.

Table 5. Limitations/areas of improvements suggested by the overviewed studies.

Limitations/Areas of Improvements	Description	Associated Studies
Technology Limitations in Clinical Application VR and AR	Face challenges in clinical application due to insufficient quality and technological constraints, hindering their broader adoption in medical settings.	[81]
Challenges to AI Acceptance in Interventional Radiology	Despite AI's potential in enhancing radiological diagnosis through VR, AR, and radio genomics, clinical acceptance in interventional radiology is hindered by obstacles that must be overcome for broader adoption.	[84]
Lack of Standardization in VR Education	While VR enhances learning in interventional radiology, the lack of research on standardizing its use across procedures underscores the need for further study and standardization in VR education.	[83]
Obstacles to AI Integration in Radiology	AI integration in radiology faces technical challenges and limitations, restricting its clinical acceptance. Overcoming these obstacles is crucial for broader adoption in radiological practices.	[88]
Infancy of Research on VR-Simulated Radiology Stations	Research on VR-simulated radiology stations is in its infancy, with limited studies on potential applications. Further research is essential to understand benefits and overcome adoption barriers.	[85]
Usability Challenges in UIs	Despite advancements, the dominance of mouse and keyboard in radiology UIs poses challenges. Designing UIs specific to radiologists is crucial for better acceptance and usability.	[87]
Cost and Ethical Concerns in VR Training	VR training faces challenges related to costs and ethical considerations. Investigating cost-effectiveness and ethical implications is necessary for informed adoption.	[89]
Clinical Integration Challenges of ER	ER's positive impact on diagnostic procedures encounters challenges in clinical integration. Addressing cost-effectiveness and integration challenges requires further research.	[90]
Challenges in Virtual Interviews	The shift to virtual interviews in residency programs presents challenges in technology adaptation and assessment. Developing strategies is crucial to overcome these challenges.	[91]
Adoption Challenges in Difficult Airway Management	Despite advancements, challenges persist in the widespread adoption of technologies in difficult airway management. Addressing guideline compliance and technology application in clinical settings is imperative.	[92]
Transition from Traditional Training to VR in Surgery	The transition to VR in surgery faces challenges such as ethical concerns and high costs. Further research and thoughtful development approaches are needed for effective integration.	[89]
Challenges in SBME Reporting Standards	While SBME is effective, improved reporting standards and centralized resource utilization are needed for broader adoption in radiation oncology training programs.	[99]
Exploratory Nature of COTS Devices in Surgery	The application of COTS devices in surgery, especially in sterile environments, remains exploratory. Further exploration is required to realize their potential in contributing to training and preparation.	[100]

4.2. Assessing Initial Assumptions: A Reflective Perspective and Comparative Analysis

Interpreting the findings derived from the initial hypotheses and primary questions posed within the narrative review, a multitude of significant considerations come to light. Firstly, scholars continue to perceive VR through both traditional [97,98] and avant-garde lenses [17,28,29], reflecting the dynamic nature of VR research. Secondly, digital radiology plays a pivotal role beyond traditional radiography, extending to various clinical activities [92,93,98]. FDA analysis reveals a significant presence of approved VR and AR devices tailored for radiological applications [63], underlining radiology's role in shaping medical imaging technologies. Despite technological advancements, the integration of VR and AR into medical practices requires caution due to regulatory limitations [64,65,69]. Only very recent progress includes Canadian Health's approval of Class 2 VR/AR devices for diagnostics [75]. While VR/AR systems promise transformation in diagnostic methodologies, their clinical implementation remains limited [64,65]. Academic discourse emphasizes thorough investigations into regulatory and ethical complexities [81], advocating for informed decision-making and collaborative oversight. Concerns such as "cyber sickness" prompt developers to focus on improving tracking and synchronized movement [82]. Caution is warranted in adopting VR/AR in healthcare, emphasizing regulatory approvals and rigorous research to address ethical and efficacy concerns.

A narrative review of reviews, which serves as a compendium of consolidated themes, supplemented by international standardization analyses—a true indicator of integration within the health domain, as proposed in our study—is crucial for assessing technology consolidation and identifying gaps and criticalities. Caution is emphasized when comparing the insights gleaned from our overview of reviews, which focuses more on consolidated themes, with the review of articles and/or primary studies conducted by Javaid et al. [17], as originally hypothesized. In the review by Javaid et al. [17], numerous themes were identified, as outlined in Table 1.

In our overview of reviews, the themes have been greatly reduced and become less specific, as expected. However, when reading together the review in [17] regarding the themes/patterns and emerging insights from this review of reviews, numerous reflections of caution have jointly emerged. Nonetheless, it is imperative to maintain a vigilant watch over the specific areas delineated in Table 1 and on the themes/emerging from this review of reviews, with particular attention to overcoming the detected problems. Should there be a discernible accumulation of consistent and pertinent medical knowledge, the prospect of undertaking targeted revisions, potentially even through systematic methodologies, emerges as a captivating avenue for further exploration and refinement of the themes detected in Table 1. The dynamic landscape of evolving technology and accumulating insights underscores the importance of ongoing scholarly engagement to meaningfully contribute to the advancement of knowledge in this field.

4.3. Advancements in Robotic Integration and Further Considerations

4.3.1. Highlights and Deepening from the Overview of Reviews

From the analysis reported in the preceding discussion, it emerges that, regarding the second question, "*3. How has virtual reality been integrated in the radiology domain with other inno-vative technologies (e.g., robotics, artificial intelligence, and augmented reality)?*", while integration with AI, VR, and AR has been extensively developed, the treatment of integration with robotics remains rather limited. In fact, only three studies [96,97,100] have touched upon the integration of VR with robotics in radiology. The study by Singhal et al. [96] and the study by Damman [97] have addressed this theme, albeit in a somewhat subtle and prospective manner. The first study [96] tackled it in Oral Medicine and Radiology, Oral Pathology, and Oral Surgery, highlighting that alongside integration with Artificial Intelligence and VR, AR robotics will also present significant potential. The second study [97], in an overview of the state-of-the-art of medical imaging processing methods, discusses the practical implications for the radiologist's daily work and future aspects, including robotics.

The study by Alvarez-Lopez et al. [100] delved into the integration of VR with robotics in a much broader context, which warrants further elaboration. Their review highlights intriguing perspectives that emerge from exploring this intersection that we resume in brief. The integration of VR and robotics in radiology presents significant promise, particularly in optimizing surgical procedures and workflow efficiency. This aspect, extensively discussed in the review [100], highlights the utilization of COTS devices for gesture recognition during surgeries, while maintaining stringent asepsis and antisepsis protocols.

The early investigations referenced in [100] delved into the feasibility of employing off-the-shelf systems equipped with various types of cameras to enable touchless interaction with medical images, particularly in critical environments like operating rooms. Among these systems, the MK and LMC emerged as top choices due to their high acceptance rates for manipulating medical data in sterile environments. Despite their benefits such as contactless operation, affordability, and robust gesture recognition capabilities, they do have drawbacks like latency issues and restricted gesture recognition.

However, both the MK and LMC have played crucial roles in enhancing workflow monitoring and collision avoidance in robotic surgery settings, as highlighted in [100]. Additionally, the Myo armband, discussed in [100], offers a wearable solution for gesture-based interaction, although its limited sampling frequency is a limitation. Nevertheless, it shows promise in improving natural user interaction and efficiency in surgical image manipulation.

The application of gesture-based off-the-shelf devices in robotic surgery faces challenges, including cost implications and technical limitations. Yet, recent studies suggest that devices like the LMC could provide cost-effective solutions for developing control interfaces in simulation environments for surgical robots, aiding in both training and actual procedures.

Furthermore, these devices have been utilized in surgical education, particularly in minimally invasive and robotic surgery, for skills learning, instrument tracking, and control interface development, offering immersive training experiences, as discussed in [100]. Ethnographic studies have provided valuable insights into gesture-based touchless interaction in surgical practices, considering social dynamics and collaborative workflows, although there is a need for objective validation studies, as highlighted in [100].

Future research in this field, as emphasized in [100], should focus on standardizing gesture-based interfaces, developing algorithms for gesture recognition and resolving issues related to temporal segmentation and spatial-temporal variability. Moreover, the development and validation of portable, low-cost virtual reality simulators for surgical training hold promise for enhancing accessibility and effectiveness in skills learning, as extensively discussed in [100]. Despite methodological limitations, exploring off-the-shelf devices in radiology and surgical practice remains an evolving area with substantial potential for improving patient care and surgical training, as discussed extensively in [100].

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.

Moreover, for completeness, some details are reported in Supplementary Materials (s.3) regarding the COTS overviewed in the study.

4.3.2. A Complementary Review

Based on the above, we decided to complement the review by analyzing any other scientific productions (beyond the reviewed ones) using the composite key in Box 1, position 3. In addition to the studies mentioned in [96,97,100], seven more studies have emerged [102–108].

In two studies conducted before the year 2000, Benabid et al. [107,108] highlighted that neurosurgery served as a fundamental platform for the development of robot applications, primarily employing multimodal image guidance. Motorized tools were regularly utilized in stereotaxy and conventional neurosurgery, utilizing databases derived from multimodal numerical images. Moreover, they foresaw integration with AR and VR.

Shi et al. [102] focuses on the application of endovascular robotic systems in robot-assisted interventional surgery, aiming to enhance surgical safety and minimize radiation exposure to surgeons. While such procedures demand a high level of skill in operating vascular interventional surgical robots, the development of a novel VR interventional training system emerges as a promising solution. This VR system, an extension of the endovascular robotic system, offers advantages over traditional training methods, improving training effectiveness and reducing educational costs. Notably, the study introduces an innovative method for catheterization modeling in interventional simulations, employing collision points to discretize the catheter and simulating its behavior as torsion-free elastic rods. This approach enhances stability, reduces computational complexity, and enables accurate simulation of catheter interaction and virtual force feedback in the proposed VR interventional training system. The effectiveness of this method is demonstrated through experimental validation.

Maresacux and Diana [103] reported how the fields of surgery, interventional radiology, and advanced endoscopy have advanced minimally invasive techniques, significantly benefiting postoperative outcomes. However, the complexity of these techniques necessitates extensive training. The integration of robotics and computer sciences offers a solution to enhance and facilitate minimally invasive approaches. The manuscript envisions a convergence of surgery, advanced endoscopy, and interventional radiology into a new hybrid specialty—hybrid image-guided minimally invasive therapies. This collaborative approach aims to maximize positive effects and minimize the iatrogenic footprint on patients. Describing the fundamental steps of this paradigm shift, the manuscript anticipates this integration as the next innovative step in advancing minimally invasive surgical therapies.

Ni et al. [104] emphasized the importance of ultrasound-guided biopsy as a fundamental but challenging skill in interventional radiology that requires intensive training for trainee radiologists, especially in needle insertion, to ensure safe procedures. This paper introduces a VR simulation system designed to enhance the training of radiologists and physicians in these procedures. Key features encompass 3D anatomical model reconstruction, data fusion of multiple ultrasound volumes and CT, realistic rendering, interactive navigation, and haptic feedback in six degrees of freedom. Users are presented with simulated ultrasound imagery, derived from actual ultrasound data, in real time, while conducting a needle placement examination into a virtual anatomical model. The system provides a lifelike haptic experience by means of a kind of robotic tool for trainees during simulated needle insertion, allowing for repeated practice without posing any risk to patients.

The study by Moix et al. [105] discusses IR as a minimally invasive procedure using thin tubular instruments guided through the patient's vascular system under X-ray imaging. The challenges in training radiologists for these procedures are outlined, noting drawbacks in existing simulation systems. The paper proposes a quality training environment for interventional radiology, comprising a VR simulation of the patient's anatomy linked to a robotic interface for haptic force feedback. The study's emphasis is on addressing the limitations of current systems, and the paper specifically focuses on the requirements, design, and prototyping of a haptic interface tailored for guide wires. The same author in [106] discusses IR, a minimally invasive surgical technique, where guidewires and catheters are navigated through the vascular system under X-ray imaging. To enhance radiologist training in this procedure, the paper proposes a computer-assisted training environment for IR. The system integrates a VR simulation of the patient's anatomy with a robotic interface offering haptic force feedback. The focus of the paper is on detailing the requirements, design, and prototyping of a specific aspect of the haptic interface dedicated to catheters. This involves a friction drive arrangement using two cylinders for translational tracking and force feedback, with an additional motor providing torque feedback. Integrated force and torque sensors in the cylinders enable direct measurement on the catheter, allowing for disturbance cancellation through a close-loop force control strategy.

The studies underscore the pivotal role of integrating VR and robotics in various medical domains. Benabid et al. [107,108] emphasize neurosurgery as a foundational platform for robotic applications, foreseeing integration with augmented reality (AR) and VR. Shi et al. [102] focus on endovascular robotic systems in interventional surgery, introducing a novel VR training system for enhanced safety. Maresacux and Diana [103] propose the convergence of surgery, endoscopy, and interventional radiology into hybrid therapies, leveraging robotics and computer sciences. Ni et al. [104] address ultrasound-guided biopsy training with a VR simulation system, while Moix et al. [105,106] discuss quality training environments for interventional radiology, integrating VR simulation and robotic interfaces.

These studies collectively showcase the potential for VR and robotics to transform medical practices, emphasizing improved safety, training efficacy, and patient outcomes.

The key emerging themes/patterns are reported in Table 6.

Table 6. Key emerging themes suggested by the overviewed studies.

Associated Studies	Key Emerging Themes	Details
Benabid et al. [107,108]	*Neurosurgery as a Platform for Robotics*	These studies highlighted neurosurgery's role in developing robotic applications, utilizing multimodal image guidance. Motorized tools were employed in stereotaxy and conventional neurosurgery, with a forecast of integration with AR/VR.
Shi et al. [102]	*Endovascular Robotic Systems in Interventional Surgery*	This study focused on endovascular robotic systems in interventional surgery. They introduced a VR interventional training system, enhancing surgical safety. The study included innovative catheterization modeling, and demonstrated effectiveness through validation.
Marescaux and Diana [103]	*Hybrid Image-Guided Minimally Invasive Therapies*	This study discussed the convergence of surgery, endoscopy, and interventional radiology into hybrid image-guided minimally invasive therapies. Integration of robotics and computer sciences was proposed to advance minimally invasive approaches.
Ni et al. [104]	*VR Simulation for Ultrasound-Guided Biopsy Training*	This study introduced a VR simulation system for ultrasound-guided biopsy training. The system featured 3D anatomical model reconstruction, data fusion, realistic rendering, interactive navigation, and haptic feedback, enhancing radiologist and physician training.
Moix et al. [105]	*Quality Training Environment for Interventional Radiology*	This study proposed a quality training environment for interventional radiology with a VR simulation linked to a robotic interface. The focus was on addressing limitations of existing systems and designing a haptic interface tailored for guide wires.
Moix et al. [106]		This study further discussed a computer-assisted training environment for interventional radiology, integrating VR simulation and a robotic interface with a specific focus on catheters. The paper detailed the design and prototyping of a haptic interface.

4.3.3. Further Considerations on the Integrations with the Robotics

During the overview of reviews on *VR in radiology*, a limitation in specific studies on robotics emerged, prompting further investigation. This limitation can be interpreted from two perspectives.

The *first perspective* concerns the role of radiology and imaging. For instance, in the intersection of robotic tele-surgery [109–111] with Virtual Reality, the role of radiology may be less pronounced since Virtual Reality often utilizes optical sensors such as video endoscopes, digital lenses, and others.

The *second perspective* relates to regulations. It is necessary to consider the intended use of the device and the role of VR, which is the focus of our overview of reviews. The MDCG 2019-11 Guidance on Qualification and Classification of Software in Regulation (EU) 2017/745—MDR and Regulation (EU) 2017/746—IVDR clarifies this aspect decisively [112]. It states that "Virtual reality technology may be used to support a remote surgeon to control a surgical robot performing the surgical procedure. Telesurgery systems should be qualified as medical devices according to the road maps in the document. Remote control software used in combination with telesurgery robots is a software that drives or influences the use of a medical device. Communication modules themselves are not medical devices. Other modules that are intended to influence the surgery procedure are qualified as medical devices".

It is evident that if VR modules are not directly used for this purpose but, for example, for other types of activities (such as mere support) and experiences, they do not fall under device regulations. Therefore, it is important in this paradigm and integration to consider both the role of radiology (whether present or not) and the intended use of the device, particularly focusing on its components and with a focus on VR, whether VR functions as a medical device or a mere component.

4.4. Synoptic Diagram

Figure 8 presents a synoptic diagram referencing the Tables and graphs included in this review. Figure 8B refers to Table 1, which imports perspectives on VR in radiology based on the review in [17] of primary articles and studies. Figure 8C refers to instruments reporting standardization in this area by the FDA: Table 2 provides a dump of the authorization register for VR/AR devices, and Figures 2 and 3. Figure 8D refers to trends described in four graphs (Figures 4–7). Opportunities and limitations are, respectively, reported in Figure 8F,G, recalling Tables 4 and 5. Following a need for further investigation on non-review studies on the integration of VR and radiology with robotics, to take stock (Figure 8H), Figure 8I refers to Table 6 with the emerged evidence. Table S1 (Figure 8) in the Supplementary Material provides the ANDJ checklist.

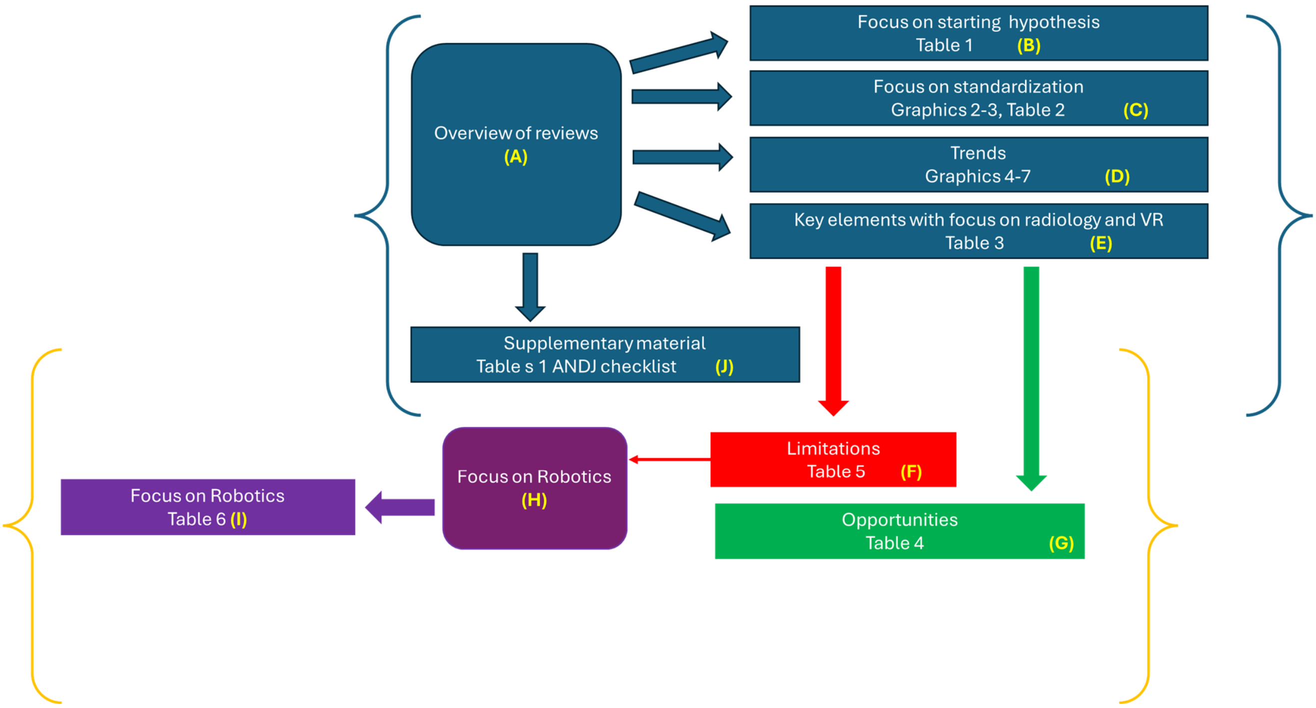

Figure 8. Synoptic diagram.

4.5. Takeaway Message

Significant initiatives have involved the integration of Virtual Reality with digital radiology, driven by the characteristics and peculiarities of the sector. The integration has also extended to other technologies such as AI and AR, with robotics playing a minor role. The underlying message strongly encourages continued progress in this field, consolidating current experiences and addressing the ongoing challenges of technological innovation.

4.6. Limitations

This study employed PubMed and Scopus databases, concentrating on review studies through a narrative review of reviews to discern emerging themes and patterns, incorporating them into the discussion. It was also complemented with other targeted searches also based on direct access to institutional websites. Subsequent targeted research on these topics, including systematic reviews, can precisely monitor the progress made. Exploring in details national databases can additionally enhance knowledge in this domain by identifying local initiatives, with a particular emphasis on standardization and regulatory compliance.

5. Conclusions

The literature highlights significant opportunities in the integration of VR with radiology, often in tandem with AR and AI in medical imaging. Key areas include advancements in medical education, potential contributions in diagnostics, extended reality applications, evolution of user interfaces, innovative approaches such as VR-simulated workstations, 3D modeling, personalized learning, and simulation-based medical education. The convergence of radiology, digital health, and VR signals a paradigm shift that could unlock innovative approaches to medical imaging and patient care. However, emerging limitations and areas for broader investigation encompass technology constraints, obstacles to AI acceptance in interventional radiology, challenges in standardizing VR education, the need for regulatory adjustments, the development of adequate norms, and ethical concerns. In the field of robotic integration, advancements in neurosurgery, endovascular robotic systems, and proposals for hybrid image-guided minimally invasive therapies show promise.

Continued research, targeted investigations, regulatory initiatives, and technological refinements are emphasized as being crucial for harnessing opportunities and addressing challenges in the evolving field of medical imaging and healthcare.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/robotics13050069/s1, The ANDJ checklist is reported in Supplementary Material (s.1). For completeness, excerpts are reported in Supplementary Materials (s.2) related to the overviewed studies refs. [81–100]. For completeness, details are reported in Supplementary Materials (s.3) regarding the COTS reported in the study overviewed in [100].

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List of Acronyms

VR	Virtual Reality
AR	Augmented Reality
FDA	Food and Drug administration
DICOM	Digital Information and Communication
PACS	Picture Archiving and Communication System
RIS	Radiology Information System
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
VAR	Virtual and Augmented Reality
ER	Extended Reality (1st definition)
XR	Extended Reality (2nd definition)
MR	Mixed Reality
HMD	Head Mounted Device
CAVE	Cave Automatic Virtual Environment
AI	Artificial Intelligence
SBME	Simulation-based medical education
UI	Unit Interface
IR	Interventional Radiology
COTS	Commercial off-the-shelf
MK	Microsoft Kinect
LMC	Leap Motion Controller

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