

Systematic Review

Immersive technology applications in radiation protection for fluoroscopy - A systematic review

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ABSTRACT

Introduction: Immersive technology is being increasingly incorporated into various professional and educational settings for occupational safety and health training. This review aims to assess the impact of immersive technology on the radiation protection (RP) of workers exposed to ionising radiation during fluoroscopy-guided procedures.

Methods: Studies were collected from six databases on 3 April 2024: PubMed, Academic Search Complete, Scopus, Web of Science Core Collection, ScienceDirect, and Engineering Village. Additionally, studies were identified through snowball sampling techniques. Eligible studies assessed RP learning via immersive technology among healthcare workers or trainees exposed to ionising radiation from fluoroscopy in operating or interventional rooms. Additionally, only original research articles published in peer-reviewed journals and written in Portuguese, Spanish, English, and French were included. The review followed PRISMA and PICo, using narrative synthesis and bibliometric analysis. Quality was assessed using the Mixed Methods Appraisal Tool checklist.

Results: Ten studies involving 358 individuals (37 % trainees/students; 63 % workers) were analysed. All assessed the usefulness of RP education/training, and most (9/10) reported an improved understanding of scattered radiation. Technologies used included virtual reality (7/10), augmented reality (2/10), and mixed reality (1/10). Radiation scatter visualisation was present in the majority (9/10) of the studies, and 1/10 combined immersive technology with clinical training.

Conclusion: These technologies enhance learning outcomes, support effective RP teaching, and optimise work practices. Integrating clinical training with RP education is essential.

Implications for practice: This study supports healthcare professionals and educators in understanding how immersive technology (virtual, augmented, and mixed reality) is being applied and evaluated in training and real work contexts. Insights into methods, outcomes, and study populations inform practical use, while bibliometric data highlight key sources and authors for future reference and collaboration.

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Abbreviations: AR, Augmented Reality; MMAT, Mixed Methods Appraisal Tool; MeSH, Medical Subject Headings; MR, Mixed Reality; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analysis; RP, Radiation Protection; VR, Virtual Reality.

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Introduction

In 2020, 24 million interventional radiology procedures were performed using fluoroscopy, marking a sixfold increase in just 12 years.^{1,2} The popularity of minimally invasive surgery in various medical specialties due to its benefits, technological development, and ease of access to equipment, has led to a significant increase in the use of fluoroscopy. Additionally, it is important to recognise that, over the years, interventional procedures have become more complex, potentially requiring longer radiation times and higher exposure doses.^{3–6}

During surgical and interventional procedures that utilise fluoroscopy, workers are positioned close to the radiation source,⁷ which may expose them to high doses (e.g., angiography, cardiac catheterisation).^{8,9} This situation also raises the issue of occupational radiation protection (RP).^{10–12} Activities involving ionising radiation are considered high-risk and are likely to pose threats to genetic heritage.¹³ Exposure to ionising radiation can damage workers' health and reduce both life expectancy and quality of life through stochastic and/or deterministic effects.^{11,14} Workers are the cornerstone of health protection in the workplace, and their health is a vital asset that must be safeguarded through preventive measures.¹⁵ They must also know how to perform activities safely.¹⁶ In fact, radiation control measures can be challenging to grasp because the invisibility of radiation makes it difficult to identify potential exposure risks.⁸ In this context, awareness and training play a critical role. Occupational exposure awareness is closely related to dose reduction, as workers become more conscious of potential exposure risks and of how to reduce them.¹⁷

Recently, immersive technology — a term that encompassing various technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR)¹⁸ — has emerged as a significant technological advancement that blurs the boundaries between the physical and virtual realms, providing users with a deeply engaging experience and a sense of immersion.^{18,19} In VR, the user is immersed in a fully computer-generated environment. In AR, digital elements are superimposed onto the real environment, allowing interaction with digital objects in a physical space and breaking down the barrier between the real and the virtual. MR represents the convergence of these two technologies, which are often confused, by merging virtual and real environments and enabling simultaneous interaction with objects in both domains.²⁰

This technology has been increasingly integrated into work and learning environments.¹⁸ Immersive technology has been applied as a visual aid in several fields, including occupational safety and health training (e.g., construction),^{21,22} medical applications related to surgical procedures and education,^{23–25} diagnostic radiography education,^{26,27} and RP simulation of work in nuclear environments (e.g., hospitals nuclear pharmacies, nuclear engineering laboratory, nuclear industry),^{28–32} among others. These technologies enhance learning experiences, promote participation in collaborative activities, and increase engagement.¹⁸

In recent years, simulation-based training has gained more prominence due to technological advances and growing attention to patient safety.³³ Consequently, this type of technology can contribute to improving both patient and worker safety. Moreover, it has the potential to deliver outcomes in RP training. RP is aligned with the Sustainable Development Goals of the 2030 Agenda, playing both a direct and indirect role in achieving various targets.³⁴ In this context, this study also aims to contribute to this cause by evaluating the existing evidence on the potential of immersive technology to improve the RP of workers exposed to ionising radiation from fluoroscopy equipment during

interventional and surgical procedures, based on the evaluation of workers or future workers. Workers are the target population of these technologies, and it is important to understand their perception when using them. To the best of our knowledge, no secondary research has yet been conducted to explore the potential of immersive technology in enhancing RP for workers exposed during fluoroscopy-guided procedures.

Methods

This systematic review was conducted in accordance with the principles established by the PRISMA model³⁵ and is registered in PROSPERO (CRD42024597437).

Research question and eligibility criteria

The review was guided by the following research question: What is the available evidence on the potential of immersive technology, applied in the field of RP, for workers exposed to ionising radiation during fluoroscopy-guided procedures, based on the evaluation of current or future professionals?

Additionally, the study addresses the following secondary questions:

- Which types of immersive technology were evaluated by workers?
- What were the characteristics of the assessed samples?
- Which evaluation methods and variables were employed?
- What were the bibliometric characteristics of the studies on this topic?

Eligibility criteria were defined according to the modified PICO strategic model, using the acronym PICO for population (P), interest (I), and context (Co)^{36,37} (Table 1).

Information resources

In the first phase, the first author identified the studies using six databases, and the second author reviewed: MEDLINE via PubMed, Academic Search Complete via EBSCOHost, Scopus, Web of Science Core Collection, ScienceDirect, and Engineering Village. The search was performed on 3 April 2024.

In the second phase, manual methods were applied to identify studies through the backwards and forward snowballing techniques based on the initial set. This procedure was adopted for all articles meeting the inclusion criteria. The backwards citation technique involved analysing the bibliographic references of the included studies, whereas the forward citation technique involved analysing subsequent studies that cited them. Traceability was recorded^{38,39} in a table.

Search strategy

A comprehensive database search was conducted using Boolean operators and special characters. Keywords were selected based on MeSH terms, relevant literature, and expert knowledge, and were adapted to each database. The keywords used in the database search were: “virtual reality”, “augmented virtuality”, “extended reality”, “augmented reality”, “mixed reality”, “immersive technology*”, “radiation protection”, “radiological protection”, and “radioprotection”. The search was limited to titles, abstracts, and keywords in Scopus and ScienceDirect, and to peer-

Table 1
Eligibility criteria based on the PICO strategic model.

PICO	Inclusion criteria	Exclusion criteria
Population (P)	- Human healthcare workers or future workers exposed to ionising radiation from fluoroscopy equipment	- Workers or prospective workers in other fields (e.g., veterinary, industrial) - Radiation from other equipment
Interest (I)	- Assessment of the application of immersive technology in the context of radiation protection	- Other training methods
Context (Co)	- Work context: operating and/or interventional rooms with fluoroscopy	- Other work contexts
Others	- Language - English, French, Spanish or Portuguese - Original research articles in peer-reviewed journals	- Language - other than those specified - Review articles

reviewed scientific journals in Academic Search Complete (see [Appendix A](#)).

Selection process

The articles were managed using Rayyan.⁴⁰ The selection process comprised three phases:

- 1) Duplicate studies were identified and removed using Rayyan, with Zotero employed as a secondary check.
- 2) The titles and abstracts of articles were evaluated in Rayyan and categorised as “include”, “exclude”, or “maybe”;
- 3) The full texts of articles deemed relevant and previously categorised as “include” and “maybe” were thoroughly reviewed. These articles were then reclassified as either “include” or “exclude” in Rayyan, with exclusion rationales documented.

The first author developed this process, and the second author revised it.

Data collection and synthesis

The data extraction process involved reviewing articles and creating a detailed table containing key information such as authors, country, year of publication, and study purpose. Additional data were collected on sample characteristics (e.g., target population, sample size, age, sex distribution), the data collection process (e.g., instrument used, validity, reliability), study design, and the variables or indicators under investigation.

The immersive technology employed, as well as the results and limitations of both the technology and the studies, were also documented. Narrative synthesis was applied to integrate findings from methodologically heterogeneous studies.⁴¹

Bibliometric data analysis was performed to map literature trends and generate indicators for the treatment and management of information and knowledge, thereby measuring scientific activity and establishing the interrelationship between scientific and technological advancement.⁴² The software used for the analyses was Microsoft Excel and VOSviewer (version 1.6.19).⁴³

Quality appraisal

The selected studies were assessed for risk of bias by the first author, with the second author reviewing the process, using the Mixed Methods Appraisal Tool (MMAT), version 2018 checklist.^{44–47} This tool was selected for its ability to assess the quality of the most common empirical study methodologies and

designs.⁴⁴ It enables the evaluation of the methodological quality of five types of studies: qualitative research, randomised controlled trials, non-randomised studies, quantitative descriptive studies, and mixed methods studies. No studies were excluded based on quality.⁴⁴ The declaration of conflict of interest and sources of support were also analysed.

Results

A total of 1159 records were identified through searches in the six databases: PubMed (n = 35), Academic Search Complete (n = 14), Scopus (n = 774), Web of Science Core Collection (n = 40), ScienceDirect (n = 253), and Engineering Village (n = 43). After applying filters in Scopus and ScienceDirect ([Appendix B](#)) and removing duplicates, 130 records remained.

Title and abstract screening excluded 109 records, leaving 21 for full-text analysis, of which 12 did not meet the eligibility criteria. Additionally, 303 records were identified through backward and forward snowballing. Of these, 15 were assessed in full text, and 4 were excluded.

A total of 10 studies were included in this review — 9 retrieved from the databases^{33,48–55} and 1 from backward snowballing.⁵⁶ The study selection process is depicted in [Fig. 1](#), with detailed exclusion reasons provided in [Appendices C–E](#).

Bibliometric analysis

The 10 included studies were published between 2009 and 2023, of which 9/10 were published between 2020 and 2023. There was an 11-year gap in publication between 2009 and 2020; however, the trend has been increasing ([Fig. 2](#)). A total of 7/10 studies had received citations. The most cited article was Bott et al.,⁵⁵ with 19 citations (see [Appendix C](#)).

The analysis also considered the prestige and impact factor of the journals, using the SCImago Journal Rank (SJR) and the Journal Impact Factor (JIF). Most studies (8/10) were published in journals ranked between Q1 and Q2 by SJR, while 6/10 were in journals ranked by JIF. One study (1/10) had no available data. The study identified via snowballing was ranked Q1–Q2 by both SJR and JIF.

The International Journal of Computer-Assisted Radiology and Surgery published 2/10 of the studies, with a Q2 ranking by JIF and Q1 by SJR (see [Appendix F](#)).

Co-authorship analysis revealed 56 authors grouped into 8 distinct clusters, with no collaboration between clusters ([Appendix G](#)). Eleven authors contributed to two studies — nine within one cluster and two within another. These two authors also published the earliest article, with one displaying an 11-year gap between publications. Authorship ranged from a single author (Fujibuchi⁵⁴) to ten authors (Takata et al.⁴⁸).

Keyword analysis, generated using the VOSviewer tool, allowed the identification of research preferences (see [Appendix H](#)). The tool highlights research trends and identifies relationships between keywords as indicators of scholarly focus. To visualise the keywords across the ten included articles, a map was created with a minimum threshold of two occurrences per keyword, resulting in 16 keywords. Two clusters were identified: a red cluster and a green cluster. The red cluster (9 items) focuses on VR, while the green cluster (7 items) focuses on AR. Both clusters were linked to RP, with VR and AR representing distinct technological emphases.

Temporal and spatial keyword analysis revealed evolving research trends. VR (red cluster) appeared in earlier studies, whereas AR (green cluster) emerged in more recent literature (see [Appendix I](#)).

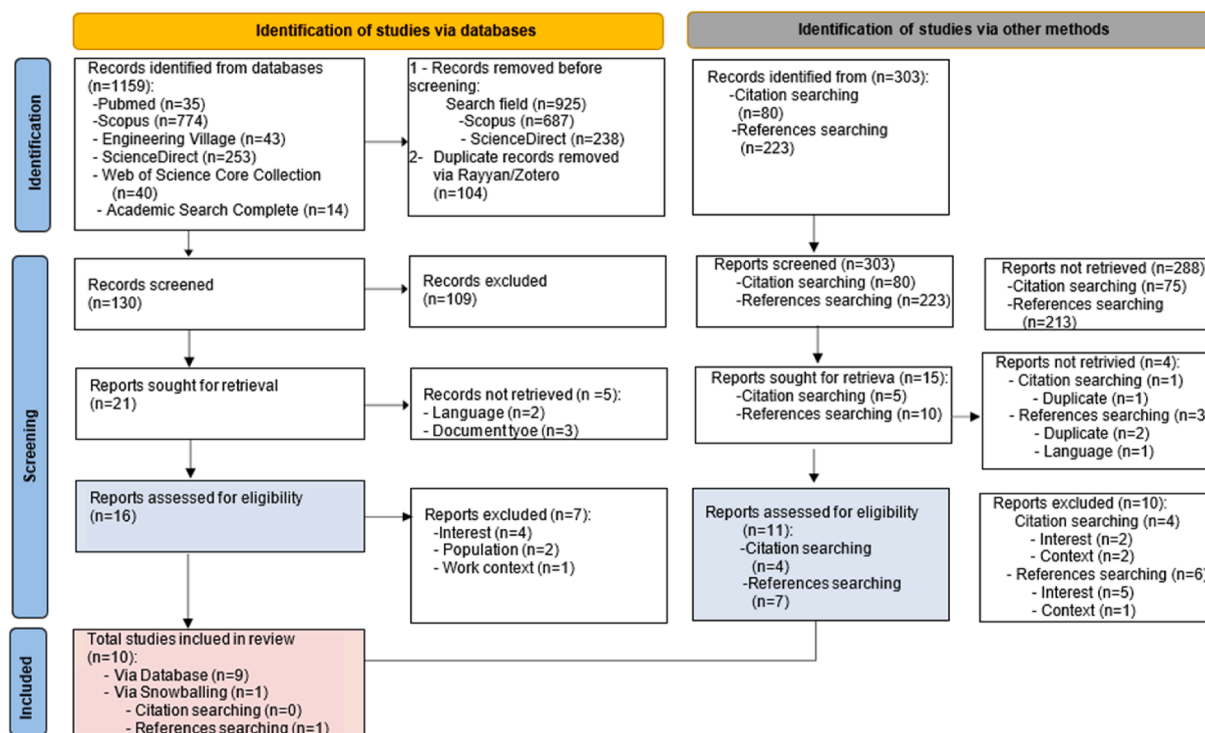


Figure 1. PRISMA flow diagram of the study selection process.

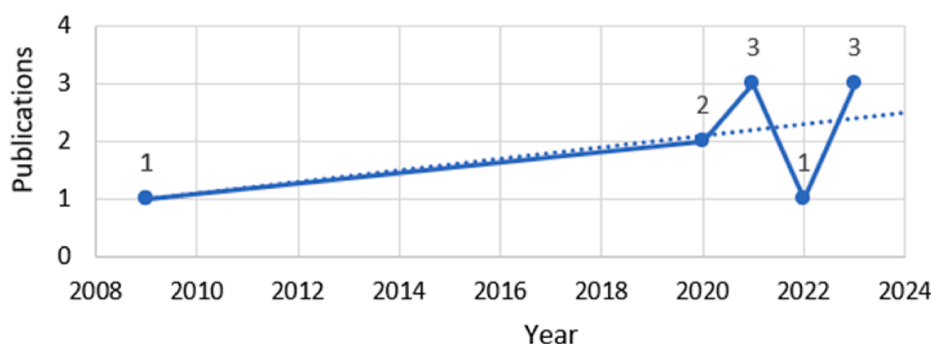


Figure 2. Annual distribution of the number of publications.

General characteristics

This review presents the findings and key features of the included studies in Table 2, in order to address the research questions.

Sample/population. This review included 358 individuals: 37 % (n = 133) trainees/students and 63 % (n = 225) professionals — physicians (2 %; n = 7), radiologists (4 %; n = 15), technicians (11 %; n = 40), nurses (23 %; n = 81), surgeons (7 %; n = 25), clinical engineers (2 %; n = 8), and other unidentified professionals (14 %; n = 49). The specialties represented included cardiology,³³ vascular surgery,^{49,50,52} interventional radiology,^{49,50,56} and orthopaedics/trauma⁵¹ (Fig. 3A).

Three studies (3/10) provided information on sex and age for 120 individuals, with a mean age between 26 and 35 years; 70 % (n = 84) were female.

Half of the studies (5/10) were conducted in Europe and half in Asia. Notably, 6/10 of the studies were conducted in different

countries across Europe (Switzerland, Germany, France, and Ireland) and in Asia (Japan and China) (Fig. 3B). Most studies (9/10) were from countries with a very high Human Development Index (HDI), and one study (1/10) from a high-HDI country (China),⁵² according to the 2024 report.⁵⁷

Data collection. The questionnaire was the most commonly used instrument (7/10) to assess the impact of the immersive technology intervention.^{48–51,53,55,56} One study (1/10) reported on the instrument's validity and reliability.⁴⁹ Fujibuchi⁵⁴ used interviews, Popovic et al.³³ employed a checklist, and Su et al.⁵² applied expert rating scales.

Half of the studies (5/10) did not report the timeframe for sample collection, while those that did were conducted between 2008 and 2022.^{48,50,53,54,56} The study by Popovic et al.³³ was non-randomised, Fujibuchi⁵⁴ was qualitative, Su et al.⁵² was randomised. The remaining studies (7/10) did not report their design.

Table 2

General characteristics of the included studies.

Coding	Author(s), (Year)	Focus study	Sample/population: 1. Target group; 2. Sample (n) (initial/response ratio/final); 3. Age ($\bar{x} \pm \sigma$) 4. Sex (δ/φ)	Data collection: 1. Instrument 2. Validity and reliability 3. Year 4. Study design	Immersive technology	Indicators/variables	Outcomes	Limitations of IT and studies	Methodological quality ^a (7 criteria)
A1	Takata et al. (2021) ⁴⁸ Japan	Real-time dose visualisation system for dose management	1. Interventional radiology – 2 radiologists, 18 radiological technologists (RT) 2. 20 3. NR 4. NR	1. Questionnaire –NASA Task Load Index (NASA-TLX): workload scores and user ratings of MR experience (five-point Likert scale) 2. NR 3. NR 4. NR	• MR (MR-DVS – Microsoft HoloLens + FDEIR)	• Workload score: mental demand; physical demand; temporal demand; performance; effort; and frustration level • User experience: dose distribution; special relations between real and virtual objects, latency between manipulation and virtual content, field of view, postural discomfort, hand manipulation, and voice interaction	• Low median overall workload score (33.50/100 – below medical tasks and computer activities) • Positive feedback: dose comprehensibility, hand manipulation, and voice interaction • Negative feedback: hardware performance (field of view and postural discomfort) • Overall satisfaction: almost all participants	• Use the patient's 4/7 own computed tomography images • The immersive capability of the current MR system inferior to VR • Tested on a single fluoroscopy system • No support for dynamic deformation of geometries (e.g., radiation shields, respiratory displacement, body motion) • Experimental demonstration	4/7
A2	Matsuzaki et al. (2021) ⁴⁹ Japan	Appropriate use of ceiling- suspended radiation shielding screens	1. Angiographyroom – 7 physicians, 11 nurses, 7 RT, 8 clinical engineers 2. 33/100 %/33 3. 33.9 $\pm$ 8.2 4. δ 23/ φ 10	1. Questionnaire Instructional Materials Motivation Survey (IMMS) 2. Yes 3. 2020 4. NR	• AR (ARKit 3)	• IMMS domains: attention, relevance, confidence, and satisfaction	• High mean scores (3.55/5) • High reliability (Cronbach's $\alpha = 0.92$) • Attention (4.77), relevance (4.64), confidence (4.57), and satisfaction (4.69) • No significant differences between professional groups • Physicians scored lower than other professions, except in confidence	• Evaluated focused only on learning motivation • Small sample size for each profession category • Limited applicability without modification for use in other rooms	6/7
A3	Lima et al. (2023) ⁵⁰ Switzerland	Evaluation of the usefulness of AR in radiation protection (RP) training	1. Fluoroscopy room – radiologists at different levels of experience 2. 11 3. NR 4. NR	1. Questionnaire 2. NR 3. NR 4. NR	• AR (Microsoft HoloLens 2 and FLUKA)	• Pre-AR: level of education, basic RP knowledge, and RP knowledge assessment • Post-AR: positive/negative aspects and applicability	• Knowledge self: assessment: 18 % recognised as accurate (knowledge gap) • Positive aspects: intuitive and relevant (35 %); deepened knowledge (18 %) • Negative aspect: difficulty handling the system due to weight (58 %); complexity in task performance (18 %)	• Small sample size • Simplicity of the proposed scenario • Restricted field of view	4/7

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Table 2 (continued)

Coding	Author(s), (Year) Country	Focus study	Sample/population: 1. Target group; 2. Sample (n) (initial/response ratio/final); 3. Age ($\bar{x} \pm \sigma$) 4. Sex (δ/φ)	Data collection: 1. Instrument 2. Validity and reliability 3. Year 4. Study design	Immersive technology	Indicators/variables	Outcomes	Limitations of IT and studies	Methodological quality ^a (7 criteria)
A 4	Süncksen et al. (2020) ⁵¹ Germany Switzerland	Scattered radiation simulation integrated into a C-arm training system	1. 25 trauma/ orthopaedic surgeons, 46 operating room personnel (ORP) 2. 71 3. NR 4. NR	1. Questionnaire 2. NR 3. 2018 (surgeons – Switzerland)/NR (ORP – Germany) 4. NR	• VR (virtX)	• Individual personal experience with a mobile C-arm • Perceived usefulness of the system for training • Impact of VR presentation of scattered radiation on understanding intraoperative radiation exposure • Preferences: most/least liked aspects	• Professional experience: surgeons – 1–34 years (Me = 5); ORP – 2–48 years (Me = 12.5) • 52 % strongly agreed that the system was useful for training • 90 % strongly agreed that it helps them understand radiation exposure • Positive aspect: realism, insightfulness and visualisation of scattered radiation • Negative aspect: visual problems and interaction difficulties	• NR	4/7
A5	Su et al. (2023) ⁵² China	Simulation- based training (ST) for competencies in RP and procedural skills	1. Endovascular procedures – trainees without prior experience 2. 24/100 %/24 (12 per group) 3. NR (groups comparable) 4. NR (groups comparable)	1. Expert raters -modified rating scales 2. NR 3. 2021 4. Randomised study	• VR (Mentice and Radiation Safety Software)	• RP performance: ST with feedback on radiation exposure (intervention group) vs without feedback (control group) • Estimated radiation exposure of automated and objective simulator metrics	• RP performance score: ST interventional group 58 vs control group 34 (+54 % improved) • Reduced radiation exposure in the intervention group: – Eye dose: 0.05 vs 0.12 mSv (–58 %) – Thyroid dose: 0.08 vs 0.18 mSv (–56 %) – Gonad dose: 0.25 vs 0.63 mSv (–60 %)	• Transferability from simulation- based training to real-life perfor- mance not assessed • Small sample size	7/7
A6	Popovic et al. (2022) ³³ France	Transferability of skills acquisition from a simulated environment to real-life settings	1. Laboratory cardiac catheterisation -trainees without prior experience in coronary angiography 2. 10 3. 26.1 $\pm$ 1.8 4. δ 5/ φ 5	1. Assessment checklist 2. NR 3. 2021–2022 4. Non-randomised, prospective study	• VR (Simbionix AngioMentor)	• Three real-life phases: baseline (before ST); 1 week post-ST, and 12 weeks post-ST • Global performance score including: – Procedural quality (cine loops, pressure curve check, catheter removal and exchange) – RP measures (operator body position, table height, patient- image distance) – Procedural metrics (contrast amount, fluoroscopic time, procedure time)	• After ST: higher global performance score, significantly lower fluoroscopy time, and more frequent use of RP measures • Radiation dose (patient and operator): significantly reduced at 1 week post-ST and remained stable at 12 weeks post-ST, except for the left eye lens dose	• Case selected based on predefined definitions • Effects of simulation vs didactic education not independently assessed • Real-life cases variability and number of cases per participant may affect validity • Influence of initial practical exposure vs combined theoretical ST not determined	6/7
A7	Rainford et al. (2023) ⁵³ Ireland	Experience of learning radiation safety in a simulated environment	1. Radiography students and medical students	1. Questionnaire adapted from a previous study 2. NR 3. NR	– • VR (Virtual Medical Coaching Ltd)	• Experience levels • Attitudes towards radiation safety dosimetry • Confidence in radiation safety: theory and practice, staff and	• 80 % enjoyed the in-person 3D VR learning experience; 55 % enjoyed the online VR experience via Zoom • 73 % reported increased confidence across all relevant	• Small sample size • Subjective measures	5/7

			2. Radiography students: 100/49 %/49 Medical students: 35/77 %/27 3. NR 4. NR	4. NR		equipment positioning, workspace optimising, and exposure parameter selection • Use of VR for radiation safety • Perceived advantages and disadvantages of VR as a learning tool	learning outcomes, with a stronger effect among medical students • 87 % recommend VR as a learning tool • 84 % agreed that it improved their understanding of radiation safety concepts and enhanced critical thinking • 68 % indicated that VR could be used as a secondary assessment tool	• Confidence is not synonymous with competence
A8	Fujibuchi (2021) ⁵⁴ Japan	Effectiveness of an RP education seminar using VR visualisation of scattered radiation	1. Graduate students – nurses, RT, radiologists, clinical technologists 2. 23 3. NR 4. NR	1. Interview survey 2. NR 3. NR 4. Exploratory, qualitative analysis	• VR (ParaView Glance and PHITS)	• Impression of RP teaching materials • Suggestions for further development of RP education resources	• RP teaching materials: understanding radiation distribution; imaging distribution in the workplace; checking exposure situation; ease of visualising scattered radiation; and acquiring new knowledge • Contents required for RP teaching materials: use of tablets and smartphones to facilitate access and understanding; training in a room to increase realism; learning how to use protective equipment (PE); and practical training simulating various radiological examinations with efficient execution, without excessive download time • Effectiveness: the effects of various devices, irradiation conditions, and PE can be examined without real-world costs • The system enabled users to more easily understand the distribution of radiation	• Use of human 6/7 voxel phantom • Large data volume required • ParaView operation complex – requiring an e-learning manual • Performance limited on low-spec terminal; efficiency of display software needs improvement
A9	Bott et al. (2009) ⁵⁵ Germany	Approach to improving education and reducing radiation hazards	1. Nurses (92 %), technical personnel (5 %), other professions (4 %) 2. 105/73 %/77 3. 35.4 ± 9.2 4. ♂8/♀69	1. Questionnaire 2. NR 3. 2008 4. NR	• VR (virtX)	• Training duration, exercises, strengths, and areas for improvement • Usefulness of PC-based training compared with traditional methods • Ease of interface use • Training with VR system and real C-arm: it is a useful addition to traditional training; the mobility of the manikin is sufficient for exercises • Realism of patient movements and imaging • Effectiveness of RP teaching (avoiding unnecessary exposure; understanding scattered radiation from image intensifier position) • Potential for hospital/organisational implementation	• Positive aspects – “high degree of realism and practical relevance, good training opportunity especially for novices, training without radiation especially in combination with correcting wrong adjustments without time pressure, simple user interface after introduction, training at a PC, presentation of the scattered radiation, comparison with an expert concerning time and radiation needed to achieve an image of sufficient quality, traffic light system, 3D-display, and different views” • 89 % rated VR training as a useful addition to traditional training • 76 % reported ease of use • 93 % agreed on integration with real C-arm	• Simulation did 5/7 not fully reproduce isodose curves or all influencing factors • Suggested improvement: more C-arm devices, operation tables, additional practice time, and further exercises • Limited manikin mobility and need for simpler interface

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Table 2 (continued)

Coding	Author(s), (Year) Country	Focus study	Sample/population: 1. Target group; 2. Sample (n) (initial/response ratio/final); 3. Age ($\bar{x} \pm \sigma$) 4. Sex (δ/φ)	Data collection: 1. Instrument 2. Validity and reliability 3. Year 4. Study design	Immersive technology	Indicators/variables	Outcomes	Limitations of IT and studies	Methodological quality ^a (7 criteria)
B1	Takata et al. (2020) ⁵⁶ Japan	Methods to visualise dose distribution with VR and estimate air dose using Monte Carlo simulations	1. Interventional radiology - 2 radiologists, 11 RT 2. 13 3. NR 4. NR	1. Questionnaire -NASA Task Load Index (NASA-TLX) for workload assessment 2. NR 3. NR 4. NR	• VR (VR- DVS + FDEIR)	• Workload score: mental demand; physical demand; temporal demand; performance; effort; and frustration level	• Manikin mobility positively rated (71 %) • Realism positively rated (78 % patient movement; 90 % images) • 79 % reported new insights for reducing unnecessary exposure • 75 % improved understanding of scattered radiation in relation to C-arm positioning • 86 % recommended delivery of virtX with new C-arm • Low median overall workload score (18.00/100 – below medical tasks and computer activities) • VR is useful for training and education • Facilitated intuitive understanding of dose propagation and distribution	• Authors note 4/7 that MR and AR may be suitable for clinical use	

Notes: A1-A9 = identified via database; B1 = identified via snowballing; n = number; NR = Not reported; MR = mixed reality; RT = radiological technologist; AR = augmented reality; VR = virtual reality; IMMS = Instructional Materials Motivation Survey; OPR = operating room personnel; Me = median; RP = radiation protection; ST = Simulation-based training; PE = protective equipment.

^a Methodological quality criteria were assessed the Mixed Methods Appraisal Tool (MMAT), version 2018. Adapted from Hong et al.⁴⁴

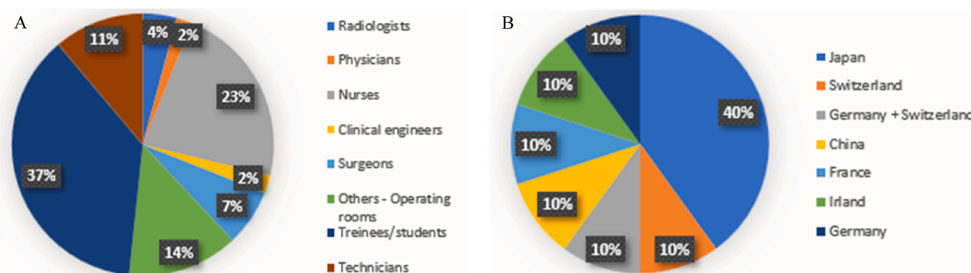


Figure 3. Sociodemographic data. (A) Professional categories of the sample. (B) Geographical distribution (%) of the countries of origin of the studies.

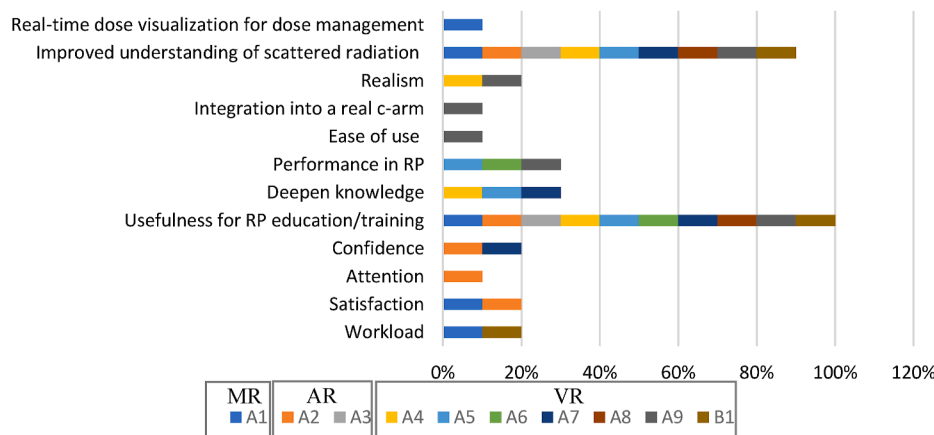


Figure 4. Distribution of variables studied in the included studies.

Note: VR = Virtual reality; MR = Mixed Reality; AR=Augmented reality; A1- Takata et al⁴⁸; A2 - Matsuzaki et al⁴⁹; A3 - Lima et al⁵⁰; A4 - Sünksen et al⁵¹; A5 - Su et al⁵²; A6 - Popovic et al³³; A7 - Rainford et al⁵³; A8 - Fujibuchi⁵⁴; A9 - Bott et al.⁵⁵; B1 - Takata et al.⁵⁶

Immersive technology

The most frequently evaluated immersive technology was VR (7/10).^{33,51-56} MR was evaluated in 1/10⁴⁸ and AR in 2/10^{49,50}. In 9/10 of the studies (except for Popovic et al.³³), the immersive technology included radiation scatter visualisation.

These technologies were applied to combine clinical training with radiation visualisation⁵² and to educate or train both workers^{48-51,55,56} and trainees/students^{33,52-54} in RP measures.

Variables studied

The included studies employed different immersive technologies: one used MR technology,⁴⁸ two applied AR,^{49,50} and seven used VR.⁵¹⁻⁵⁶ Workload and real-time dose visualisation for dose management were investigated in 2/10 studies (MR⁴⁸ and VR⁵⁶). Satisfaction with technology was assessed in 2/10 studies, including Takata et al.⁴⁸ (MR) and Matsuzaki et al.⁴⁹ (VR), with the latter also examining attention (1/10). Confidence was evaluated in 2/10 studies using VR.^{49,53} The usefulness of RP education was reported in all studies. In 3/10 studies, all using VR, the variable deepening of knowledge⁵¹⁻⁵³ and RP performance^{33,52,55} were assessed. One study (1/10) examined ease of use and integration with a real C-arm using VR.⁵⁵ Realism was analysed in 2/10 studies, both using VR.^{51,55} Improved understanding of scattered radiation was reported in 9/10 studies (except Popovic et al.³³) (Fig. 4).

Outcomes. A meta-analysis was not conducted due to the marked heterogeneity of the included studies. Substantial differences were observed in study design, populations, types of immersive technologies applied (VR, AR, MR), intervention characteristics, outcome measures, and evaluation methods. These methodological and contextual variations meant that statistical pooling of the

data would not have been appropriate or reliable. For this reason, a narrative synthesis was considered the most suitable approach, enabling us to capture and interpret the breadth of findings while respecting the differences across studies.

Median workload scores were 33.50 for MR⁴⁸ and 18.00 for VR,⁵⁶ both lower than those reported for medical tasks (50.60) and computer activities (54.00).⁴⁸ Overall, MR workload was 46 % higher than VR. The average median workload score across immersive technology was 25.75 ± 11 , representing a 49 % and 52 % reduction compared with medical tasks and computer activities, respectively.

Nine studies evaluating immersive technology for understanding radiation doses reported positive feedback. The real-time dose visualisation system for dose management received positive feedback for dose comprehensibility, hand manipulation, and voice interaction, but negative feedback regarding field of view and postural discomfort; hardware improvements were suggested.⁴⁸ Immersive tools also showed potential for demonstrating the benefits of protective equipment in minimising exposure, with a high motivation score among workers to learn about the correct use of ceiling-suspended RP screens.⁴⁹ Their usefulness in teaching radiologists was also demonstrated, improving practical knowledge consolidation.⁵⁰ These tools further supported understanding of intraoperative exposure to scattered radiation, illustrating concepts such as the law of distance, optimal positioning to minimise dose, and the effects of beam collimation. More than 80 % of participants rated them as helpful.⁵¹

Simulation training effectively develops fundamental skills for endovascular interventions and facilitates the acquisition of RP behaviour when feedback on radiation safety practices is provided, thereby reducing exposure.⁵² A consistent and standardised

simulation learning scheme enhances technical skill acquisition, promotes a better understanding of ionising radiation exposure, and improves awareness of occupational exposure. This results in higher performance scores, shorter fluoroscopy time, more frequent use of RP measures, and consistently lower radiation dose³³

Image acquisition simulation, covering patient positioning and scattered radiation, was positively rated for imparting RP knowledge. In total, 78 % of respondents found it sufficiently realistic, and 79 % reported acquiring new knowledge on avoiding unnecessary radiation exposure.⁵⁵ Radiation dosimetry software supports active student learning, with 73 % reporting increased confidence in RP and improved knowledge, understanding, and clinical readiness.⁵³ Similarly, 3D and 4D scatter visualisation enhanced comprehension of radiation behaviour, propagation and mitigation methods.⁵⁴

Negative aspects were mainly related to hardware performance. Reported difficulties included headset weight in AR,⁵⁰ postural discomfort in MR,⁴⁸ and a limited field of view in MR⁴⁸ and VR.⁵¹ Software-related issues included interaction difficulties in VR.^{51,55} Most studies regarded these weaknesses as opportunities for improvement. A common limitation across studies was the small sample size.

Risk of bias assessment. The MMAT appraisal (see Appendix J) indicated that all studies address a clear research question and collect adequate data. Four studies (4/10) were rated as high quality (≥ 75 % of criteria fulfilled),^{33,49,52,54} including one that achieved 100 % compliance,⁵² while six (6/10) were rated as moderate quality (50–75 %).^{48,50,51,53,55,56} None were classified as low quality (< 50 %). Seven studies (7/10) did not explicitly report their design and were therefore classified as quantitative.

The main methodological limitations were: the unclear use of validated and reliable outcome measures in seven studies (7/10, criteria 1.2 and 4.3)^{48,50,51,53,55,56,58}; incomplete reporting of non-respondents in four studies (4/10, criterion 4.4)^{48,50,51,56}; and issues concerning the representativeness of the target population (criteria 3.1 and 4.2), which was unclear in five studies (5/10)^{33,48,51,55,56} and judged as not representative due to the small sample size in three studies (3/10).^{49,50,53}

No evidence of reporting bias was identified. Six studies (6/10) explicitly declared no conflict of interest,^{33,48,49,51,53,56} whereas the remaining studies did not provide a statement. Fujibuchi⁵⁴ reported public funding, Sünksen et al.⁵¹ reported foundation support, and Takata et al.⁵⁶ acknowledged partial support from the Japan Society for the Promotion of Science.

Discussion

Training has been shown to positively affect knowledge, risk perception, safety commitment, and safety behaviour.⁵⁹ Safety education and training are considered essential strategies for improving safety performance,^{59,60} with ongoing team education and training being key factors. A lack of basic and specialised knowledge of RP can lead to negative attitudes and adversely affect workers' health.⁶¹ This review found that new approaches to education and training can be valuable tools to increase interactivity, consolidate knowledge, behaviours, and skills, and improve RP measures to minimise exposure.

Students and workers from different countries, medical specialities, and contexts were included, reflecting geographical diversity and varied perspectives. Feedback on the usefulness of these technologies in education was unanimously positive. These tools also appear to be taking initial steps in terms of usability for real-time dose management. Takata et al.⁴⁸ explored this field with

an experimental demonstration. Feedback was favourable for dose comprehensibility, manual manipulation, and voice interaction, but less so for usability due to hardware-related issues. However, the authors noted that these aspects could be improved.

The “As low as reasonably achievable” (ALARA) principle is often conveyed through lectures and technical measures to minimise exposure.⁵² The most common used training methods are “on-the-job training” with patients and RP education through passive approaches, such as lectures.³³ These practices are limited by the health risks associated with exposure.⁵² For training to be effective, methods must be adapted to the realities of the organisation and the work environment. Determinants of behaviour change should be addressed, and training techniques should actively involve workers, as these are considered the most effective in promoting safer behaviours.⁵⁹ Consequently, these factors must be considered when planning RP training.

Immersive technologies contribute to active learning. RP Training should ensure workers acquire a solid foundation in RP principles and knowledge of equipment, thereby supporting the development of new skills and attitudes. Education is essential to promote the optimisation of clinical protocols and dose reduction. Radiation-exposed workers should have substantial knowledge of RP regulations and a comprehensive understanding of factors influencing patient and occupational dose to minimise the harmful effects of ionising radiation.⁶² Training should emphasise how to minimise exposure, instil confidence and a sense of safety, and improve working conditions, always adhering to RP principles.⁶³ Operator training level has a direct impact on radiation exposure, making the establishment of a culture of radiation reduction essential.¹⁹

Simulation using immersive technology provides safe environments for trainees, offering two benefits: facilitating skill acquisition for clinical training and reinforcing RP measures to be applied during training. Visualisation of scattered radiation is still at an early stage, but results are promising. Moreover, hands-on simulation-based training using VR simulators is more effective, safer, and less expensive than training in real work contexts.⁵²

The dynamic keyword co-occurrence network reveals a more recent cluster for AR and an earlier one for VR, consistent with their technological timelines – VR emerging in the 30s, and AR differentiating from VR in the 90s. Between 2009 and 2020, no studies applied these techniques to RP in this context. However, publication activity peaked in 2021 and 2023, likely driven by the rapid adoption of digital training tools during the COVID-19 pandemic^{26,27,64} and the growing interest in RP as a result of recent epidemiological studies on workers' health,^{65,66} international recommendations^{11,67} and clinical practice guidelines^{68,69} highlighting the need for improved RP training.

Previous research has shown that workers often lack RP training.^{61,70–75} A poor RP culture is evidenced by a reluctance to use protective equipment and dosimeters, as well as limited knowledge of other RP strategies. Experts recommended RP supervision, training, and practice strategies through postgraduate and continuing education.⁷⁶ A European study on urologists' knowledge and attitudes towards ionising radiation also revealed limited awareness of protection, recommending radiation safety throughout medical careers.⁷⁷ A systematic review similarly showed that most participants had only average knowledge, with 60 % demonstrating positive attitudes, and RP-related practices were often only moderate.⁷⁸

This review found that immersive technology can increase worker confidence.^{49,53} The literature also indicates that the lack of knowledge and training contributes to stress, particularly among less experienced workers, who are more susceptible to negative emotions.⁶¹ Research highlights an inverse relationship

between knowledge, attitudes, and self-protection practices, and workplace stress.⁷⁹ Limited knowledge of radiation tends to increase anxiety, which is associated with greater psychological distress.⁸⁰ Immersive technology can therefore play a key role in reducing psychosocial risks linked to inadequate RP training and knowledge gaps.

The positive impact of immersive technologies in fluoroscopy training mirrors findings in radiography education, where VR simulation has been shown to outperform physical simulation in patient positioning, equipment handling, exposure selection, image evaluation, and clinical examination.^{81,82} These tools also enhance students' confidence in radiologic practice, with positive feedback from learners.²⁷

This review contributes by examining new approaches to education and training using immersive tools, which can increase interactivity and consolidate knowledge. It should also be noted that these findings may, in part, reflect technological advances and the growing availability and diversification of hardware and software, which have made these technologies increasingly accessible²⁰ and cost-effective.^{83,84}

This study has limitations that must be considered, including a small number of studies and the heterogeneity arising from different IT, variations in research scenarios, study design, intervention duration, teaching methods, and diverse populations with varying experience levels and medical specialities. Other limitations include sample size, response rate, interpretation bias, biased or dishonest responses, and concerns with instrument validity and reliability. Additionally, language and location biases may exist due to the exclusion of non-understood languages, lower-visibility journals, and grey literature. Grey literature databases were not searched directly; instead, we employed snowballing of references and citations to capture additional relevant studies, including some grey literature and lower-visibility journals. Another limitation concerns the strength of the evidence. Although the methodological quality of the included studies was generally acceptable, with four rated as high and six as moderate, recurring problems — including unclear use of validated outcome measures, incomplete reporting of non-respondents, small sample sizes, and unclear sample representativeness — weaken confidence in the findings. In addition, the heterogeneity of study designs, with only one randomised trial identified, further reduces the certainty of the evidence. Based on the MMAT assessment and the narrative synthesis, the findings should therefore be interpreted with caution as preliminary yet consistent evidence that requires confirmation through further high-quality research.

Future research should explore the influence of these technologies on RP culture, economic outcomes, and return on investment in healthcare and education. Existing studies have not evaluated long-term effects (beyond 12 weeks) on worker dose. Further work could address this gap and examine satisfaction and usability using validated instruments for the Portuguese population. We anticipate that radiation visualisation technologies — making invisible radiation visible in real-world settings — will become practical tools to enhance awareness, improve dose management during procedures, and minimise exposure and associated health effects.

Conclusion

Immersive technology has considerable potential to enhance the effectiveness of RP training by supporting control measures and optimising work practices. Integrating RP training with radiation visualisation through immersive technology, particularly in fluoroscopy procedures, is both innovative and essential. Combining clinical training with RP education using these tools can contribute to reducing ionising radiation exposure for both patients and healthcare professionals. These findings may guide the development of more effective educational strategies, support the advancement of next-generation RP learning environments, and promote safer practices in fluoroscopic imaging.

Ethics approval and consent to participate

Not applicable.

Availability of data

Data required for this study is available from https://docs.google.com/spreadsheets/d/1GL9x_d92bLcL2YyUmVFSJU6gltayUEx/edit?usp=drive_link&oid=114964709382943245472&rtpof=true&sd=true.

Author contributions

SV: Conceptualisation, Methodology, Investigation, Writing-Reviewing and Editing.

MR: Reviewing and Editing.

JS: Reviewing and Editing.

MVS: Supervision, Reviewing and Editing.

Generative AI use

Not applicable.

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Conflict of interest statement

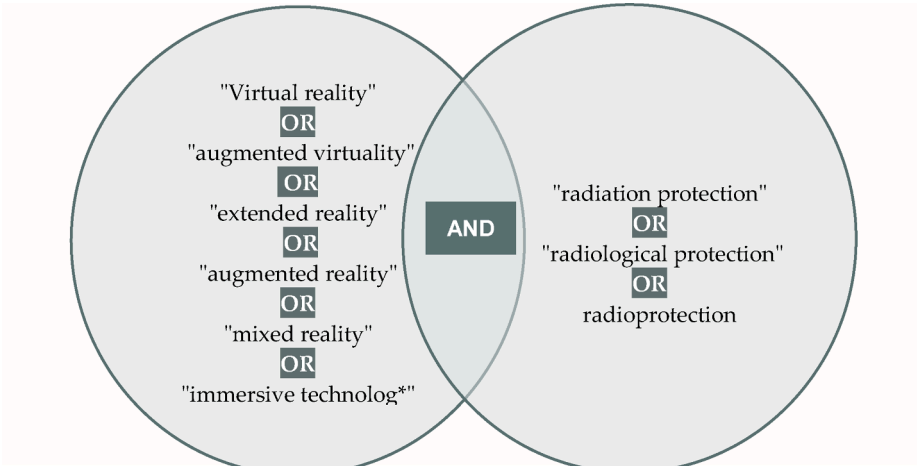
None.

Acknowledgements

Not applicable.

Appendix A

Scheme of the keywords (the search represents the intersection of the two sets of keywords) and search strategy



Search strategy

Keywords/Mesh	Search descriptors	Database	Filters	
			Search field	Others
Keywords	("Virtual reality" OR "augmented virtuality" OR "extended reality" OR "augmented reality" OR "mixed reality" OR "immersive technolog*") AND ("radiation protection" OR "radiological protection" OR radioprotection)	• MEDLINE (through PubMed) • Scopus Web of Science Core Collection • Academic Search Complete (through EBSCOhost) • Engineering Village • ScienceDirect	No Yes No No No Yes	No No No journals peer-reviewed No No
	("Virtual reality" OR "augmented virtuality" OR "extended reality" OR "augmented reality" OR "mixed reality" OR "immersive technology") AND ("radiation protection" OR "radiological protection" OR radioprotection)			
MeSH	("Augmented Reality"[MeSH] OR "Virtual Reality"[MeSH]) AND ("Radiation Protection"[MeSH])	• MEDLINE (through PubMed)	NA	No

NA= Not applicable

Appendix B

Search results as of 3 April, 2024

Search results as of 3 April, 2024						
Keywords/Mesh	Search descriptors	Database	Results			Final
			No Filters	With filters		
				Search field	Others	
• Keywords	("Virtual reality" OR "augmented virtuality" OR "extended reality" OR "augmented reality" OR "mixed reality" OR "immersive technolog*") AND ("radiation protection" OR "radiological protection" OR radioprotection)	• MEDLINE (through PubMed)	25	--	--	25
		• Scopus	774	87	--	87
				Title, abstract, keywords		
		• Web of Science Core Collection	40	--	--	40
		• Academic Search Complete (through EBSCOhost)	14	--	14 (Scientific journals peer-reviewed)	14
		• Engineering Village	43	--	--	43
		• ScienceDirect	253	15	--	15
	("Virtual reality" OR "augmented virtuality" OR "extended reality" OR "augmented reality" OR "mixed reality" OR "immersive technology") AND ("radiation protection" OR "radiological protection" OR radioprotection)			(Title, abstract or author-specified keywords)		
• Mesh	("Augmented Reality"[Mesh] OR "Virtual Reality"[Mesh]) AND ("Radiation Protection"[Mesh])	• MEDLINE (through PubMed)	10	--	--	10
Results:						
N° of records included			1159	234	234	234
N° of records deleted				925	0	925

Appendix C

Studies included from databases

Reference	Year of publication	References (n)	Citations (n)
A1 Takata, T., Nakabayashi, S., Kondo, H., Yamamoto, M., Furui, S., Shiraishi, K., Kobayashi, T., Oba, H., Okamoto, T., & Kotoku, J. (2021). Mixed Reality Visualization of Radiation Dose for Health Professionals and Patients in Interventional Radiology. <i>Journal of Medical Systems</i> , 45(4), 38. https://doi.org/10.1007/s10916-020-01700-9	2021	19	10
A2 Matsuzaki, S., Moritake, T., Morota, K., Nagamoto, K., Nakagami, K., Kuriyama, T., & Kunugita, N. (2021). Development and assessment of an educational application for the proper use of ceiling-suspended radiation shielding screens in angiography rooms using augmented reality technology. <i>European Journal of Radiology</i> , 143, 109925. https://doi.org/10.1016/j.ejrad.2021.109925	2021	36	9
A3 Lima, T. V., Figueiredo Pohlmann Simões, R., Heinrich, M., Kreienbühl, T., Wetzel, R., & Roos, J. E. (2023). Usefulness of augmented reality in radiological protection education and training for interventional radiologists. <i>The British Journal of Radiology</i> , 96(1145). https://doi.org/10.1259/bjr.20221075	2023	9	0
A4 Sünksen, M., Bott, O. J., Dresing, K., & Teistler, M. (2020). Simulation of scattered radiation during intraoperative imaging in a virtual reality learning environment. <i>International Journal of Computer Assisted Radiology and Surgery</i> , 15(4), 691–702. https://doi.org/10.1007/s11548-020-02126-x	2020	20	10
A5 Su, P., Zhu, Z., He, J., He, R., Feng, H., Du, P., Lönn, L., Konge, L., & Yin, F. (2023). Focus on Radiation Protection Improves Both Correct Behavior and Procedural Performance During Simulation-Based Training – A Randomized Comparison. <i>Annals of Vascular Surgery</i> , 89, 302–311. https://doi.org/10.1016/j.avsg.2022.10.003	2023	30	0
A6 Popovic, B., Varlot, J., Girard-Bertrand, B., Basile, J. L., Thouvenot, C., Fay, R., Villani, N., Tran, N., & Camenzind, E. (2022). Impact of Simulation-Based Training on Radiation Exposure of Young Interventional Cardiologists. <i>American Journal of Cardiology</i> , 181, 25–31. https://doi.org/10.1016/j.amjcard.2022.07.014	2022	22	0
A7 Rainford, L., Tcacenco, A., Potocnik, J., Brophy, C., Lunney, A., Kearney, D., & O'Connor, M. (2023). Student perceptions of the use of three-dimensional (3-D) virtual reality (VR) simulation in the delivery of radiation protection training for radiography and medical students. <i>Radiography</i> , 29(4), 777–785. https://doi.org/10.1016/j.radi.2023.05.009	2023	29	6
A8 Fujibuchi, T. (2021). Radiation protection education using virtual reality for the visualisation of scattered distributions during radiological examinations. <i>Journal of Radiological Protection</i> , 41(4), S317–S328. https://doi.org/10.1088/1361-6498/ac16b1	2021	16	17
A9 Bott, O. J., Wagner, M., Duwenkamp, C., Hellrung, N., & Dresing, K. (2009). Improving education on C-arm operation and radiation protection with a computer-based training and simulation system. <i>International Journal of Computer Assisted Radiology and Surgery</i> , 4(4), 399–407. https://doi.org/10.1007/s11548-009-0322-1	2009	10	19
Total		223	80

Notes: A1-A9 – coding the sources databases;

Appendix D

Studies excluded from databases

	Reference	Reason for exclusion
C1	Wagner, M., Duwenkamp, C., Ahrens, C. A., Stürmer, K. M., Dresing, K., & Bott, O. J. (2009). virtX: ein Lehr-und Lernsystem für mobile Röntgengeräte zur Verbesserung der Ausbildung im Strahlenschutz virtX: a CBT-system for mobile image intensifier systems to improve the radiation protection training. <i>GMS Medizinische Informatik, Biometrie Und Epidemiologie</i> , 5(1), 1–7. ISSN 1860-9171 Language	
C2	Loy Rodas, N., Barrera, F., & Padoy, N. (2017). See It with Your Own Eyes: Markerless Mobile Augmented Reality for Radiation Awareness in the Hybrid Room. <i>IEEE Transactions on Biomedical Engineering</i> , 64(2), 429–440. https://doi.org/10.1109/TBME.2016.2560761	Interest – without evaluation by workers/students (prototype)
C3	Loy Rodas, N., & Padoy, N. (2014). 3D Global Estimation and Augmented Reality Visualization of Intra-operative X-ray Dose (pp. 415–422). https://doi.org/10.1007/978-3-319-10404-1_52	Interest – without evaluation by workers/students (prototype)
C4	Fujibuchi, T., Ueda, K., Kadoyanagi, S., Ueno, D., & Nakamura, C. (2019). Examination of Application to Radiation Protection Education by Four-dimensional Visualization of Scatter Distribution in Radiological Examination Using Virtual Reality. <i>Japanese Journal of Radiological Technology</i> , 75(11), 1297–1307. https://doi.org/10.6009/jjrt.2019_JSRT_75.11.1297	Language
C5	Nasr, B., Guyomard, B., Visvikis, D., & Bert, J. (2023). Radiation protection training by Monte Carlo Simulation and virtual reality. <i>Annals of Vascular Surgery</i> , 96, 11. https://doi.org/10.1016/j.avsg.2023.07.022	Document type – conference paper
C6	Arakawa, H., Fujibuchi, T., Kaneko, K., Okada, Y., & Tomisawa, T. (2024). Radiation-training system with a custom survey-meter mock-up in a browser-based mixed reality environment. <i>Nuclear Engineering and Technology</i> . https://doi.org/10.1016/j.net.2024.01.057	Interest – without evaluation by workers/students (prototype)
C7	Bridge, P., Trapp, J. V., Kastanis, L., Pack, D., & Parker, J. C. (2015). A virtual environment for medical radiation collaborative learning. <i>Australasian Physical & Engineering Sciences in Medicine</i> , 38(2), 369–374. https://doi.org/10.1007/s13246-015-0348-3	Context – no fluoroscopy
C8	Louka, M.N.; Rindahl, G. (2010). A comparative study of radiation visualization techniques for interactive 3D software applications. 7th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies 3(0), 1952-1966.	Document type – conference paper
C9	Nishi, K., Fujibuchi, T., & Yoshinaga, T. (2022). Development and evaluation of the effectiveness of educational material for radiological protection that uses augmented reality and virtual reality to visualise the behaviour of scattered radiation. <i>Journal of Radiological Protection</i> , 42(1), 011506. https://doi.org/10.1088/1361-6498/ac3e0a	Context – no fluoroscopy
C10	Guo, Y., Mao, L., Zhang, G., Chen, Z., Pei, X., & Xu, X. G. (2020). Conceptual design and preliminary results of a vr-based radiation safety training system for interventional radiologists. <i>Radiation Protection Dosimetry</i> , 190(1), 58–65. https://doi.org/10.1093/rpd/ncaa082	Interest – without evaluation by workers/students (prototype)
C11	Edward, W. T. H., Marco, T. S. Y., Wendy, F. Y. Y., & Sharon, L. S. Y. (2022). Enhance the Learning Experience through the use of Interactive Pedagogies Methodology in Radiation Protection. <i>Journal of Medical Imaging and Radiation Sciences</i> , 53(4), S42. https://doi.org/10.1016/j.jmir.2022.10.137	Document type – conference paper
C12	Popovic, B., Varlot, J., Girard Bertrand, B., Metzendorf, P. A., Camenzind, E., Guionnet, C., Basile, J. L., Thouvenot, C., & Villani, N. (2022). Simulator training to minimize ionizing radiation exposure in the catheterization laboratory. <i>Archives of Cardiovascular Diseases Supplements</i> , 14(1), 120. https://doi.org/10.1016/j.acvdsp.2021.09.270	Document type – conference paper

Notes: C1-C12 – coding the sources databases

Appendix E

Traceability of identification of studies through snowballing

Available in: https://docs.google.com/spreadsheets/d/1GL9x_d92bLcL2YyjUmVFSJU6gltayuEx/edit?usp=drive_link&ouid=114964709382943245472&rtpof=true&sd=true

Snowballing (Traceability)														
Studies included			Backward (References)											
Study	Author(s)	Source	Total	Eligible	Author(s)	Source	Study originated	Included	Excluded	Duplicate	Reason	Interest	Content	Language
A1	Takata et al., 2021	https://link.springer.com/article/10.1007/s10107017115	19	1	Takata et al., 2020	https://www.ijstage.ist.go.jp/article/Interven	B1	1	0	0	Database included			
B1	Takata et al., 2020	https://www.ijstage.ist.go.jp/article/Interven	32	3	Bott et al., 2009	https://doi.org/10.1007/s11549-009-0322-1						1		
					Loy Rodas & Padoy, 2015	https://www.scopus.com/record/display.uri?https://www.scopus.com/record/display.uri?		0	1					
					Loy Rodas et al., 2017	https://ieeexplore.ieee.org/document/7746300								
A2	Matsuzaki et al., 2021	https://doi.org/10.1016/j.ejrad.2021.103925	36	1	Loy Rodas & Padoy, 2015	https://www.scopus.com/record/display.uri?https://www.scopus.com/record/display.uri?		0	1				1	
A3	Lima et al., 2023	https://doi.org/10.1259/bjr.20221075	9	1	Nishi et al., 2022	https://iopscience.iop.org/article/10.1088/136		0	1					1
A4	Sünksen et al., 2020	https://link.springer.com/article/10.1007/s11549-020-00000-0	20	1	Rodas & Padoy, 2015	https://www.scopus.com/record/display.uri?https://www.scopus.com/record/display.uri?		0	1				1	
A5	Su et al., 2023	https://www.sciencedirect.com/science/article/pii/S0969813723000000	30	0				0	0					
A6	Popovic et al., 2023	https://www.sciencedirect.com/science/article/pii/S0969813723000000	22	0				0	0					
A7	Rainford et al., 2023	https://www.sciencedirect.com/science/article/pii/S0969813723000000	29	2	Takata et al., 2021	https://link.springer.com/article/10.1007/s10107017115		0	2	1	Database included		1	
					Guo et al., 2020	https://www.scopus.com/record/display.uri?https://www.scopus.com/record/display.uri?								
A8	Fujibuchi et al., 2021	https://iopscience.iop.org/article/10.1088/136	16	1	Fujibuchi et al., 2019	https://europepmc.org/article/med/31749455		0	1					1
A9	Bott et al., 2009	https://link.springer.com/article/10.1007/s10107017115	10	0				0	0					

Studies included			Forward (Citations)										
Study	Author(s)	Source	Total	Eligible	Author(s)	Source	Study originated	Included	Excluded	Duplicate	Reason	Interest	Context
A1	Takata et al., 2021	https://link.springer.com/article/10.1007/s10107017115	10	1	Nishi et al., 2022	https://iopscience.iop.org/article/10.1088/1367-2645/22/12/123001		0	1				1
C1	Takata e al., 2020	https://www.ijstage.ist.go.jp/article/Interven/2020/1/1/Interven-2020-1-1-1	9	1	Takata et al., 2021	https://link.springer.com/article/10.1007/s10107017115		0	1	1	Database included		
A2	Matsuzaki et al., 2021	https://doi.org/10.1016/j.ejrad.2021.103925	9	0				0	0				
A3	Lima et al., 2023	https://doi.org/10.1259/bjr.20221075	0	0				0	0				
A4	Sünksen et al., 2020	https://link.springer.com/article/10.1007/s11549-020-00000-0	10	1	Nishi et al., 2022	https://iopscience.iop.org/article/10.1088/1367-2645/22/12/123001		0	1				1
A5	Su et al., 2023	https://www.sciencedirect.com/science/article/pii/S0969813723000000	0	0				0	0				
A6	Popovic et al., 2023	https://www.sciencedirect.com/science/article/pii/S0969813723000000	0	0				0	0				
A7	Rainford et al., 2023	https://www.sciencedirect.com/science/article/pii/S0969813723000000	6	0				0	0				
A8	Fujibuchi et al., 2021	https://iopscience.iop.org/article/10.1088/1367-2645/22/12/123001	17	0				0	0				
A9	Bott et al., 2009	https://link.springer.com/article/10.1007/s10107017115	19	2	Guo et al., 2020	https://www.scopus.com/record/display.uri?https://www.scopus.com/record/display.uri?		0	2			1	
					Rodas & Padoy, 2015	https://link.springer.com/article/10.1007/s10107017115						1	

Appendix F

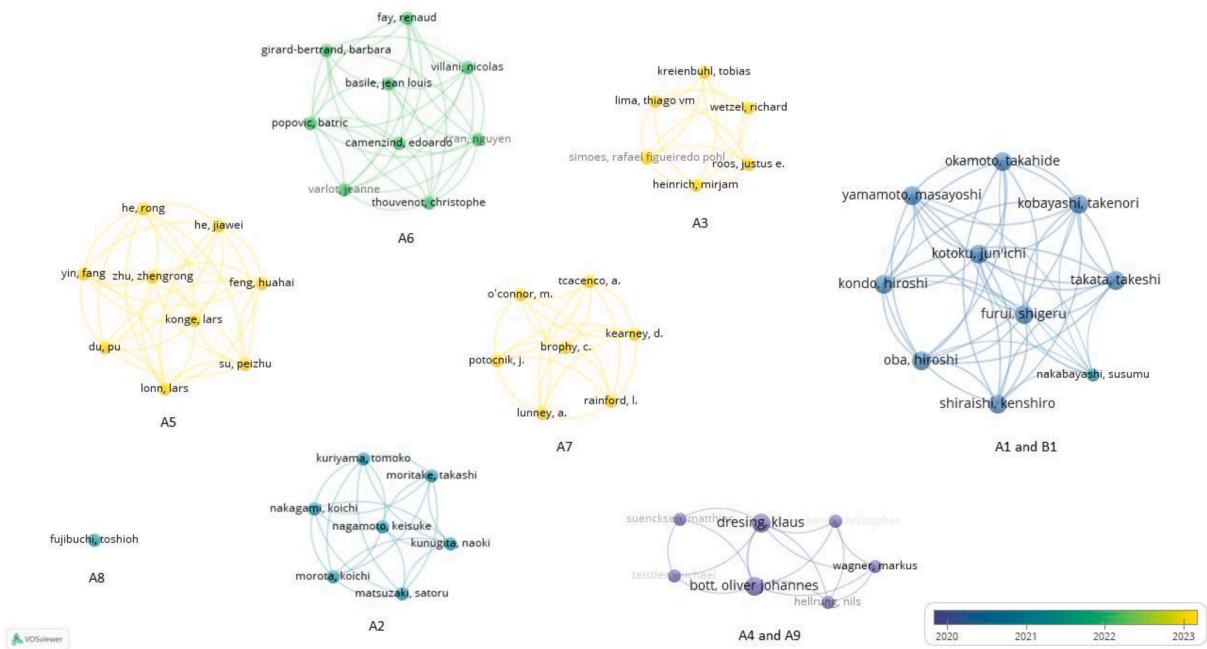
Analysis of publications

Journal	Author(s)	Studies (n)	SJR*/JIF# Quartile (n)	Database (%)	Snowballing (%)	Total (%)
International Journal of Computer Assisted Radiology and Surgery	[1]	2	Q1/Q2	20%		20%
Interventional Radiology	[2]					
European Journal of Radiology	[3]	1	ND/ND	10%		10%
Journal of Medical Systems	[4]	1	Q1/Q2	10%		10%
Journal of Radiological Protection	[5]	1	Q1/Q1		10%	10%
Radiography	[6]	1	Q3/Q1	10%		10%
American Journal of Cardiology	[7]	1	Q1/Q2	10%		10%
Annals of Vascular Surgery	[8]	1	Q1/Q3	10%		10%
The British Journal of Radiology	[9]	1	Q2/Q3	10%		10%
Total (%)	[10]	1	Q1/Q3	10%		10%
[Q1-Q2] - SJR*/JIF# Quartile			8*/6#	70*/60#	10*/10#	80*/60#
[Q3-Q4] - SJR*/JIF# Quartile			1*/3#	10*/30#	-	10*/30#
ND - SJR*/JIF# Quartile			1*/1#	10*/10#	-	10*/10#

*SJR - SCImago Journal Rank seen on <https://www.scimagojr.com/>; #JIF - Journal Impact Fact seen on <https://jcr.clarivate.com/> in 28/04/2024; ND=not discriminated

Appendix G

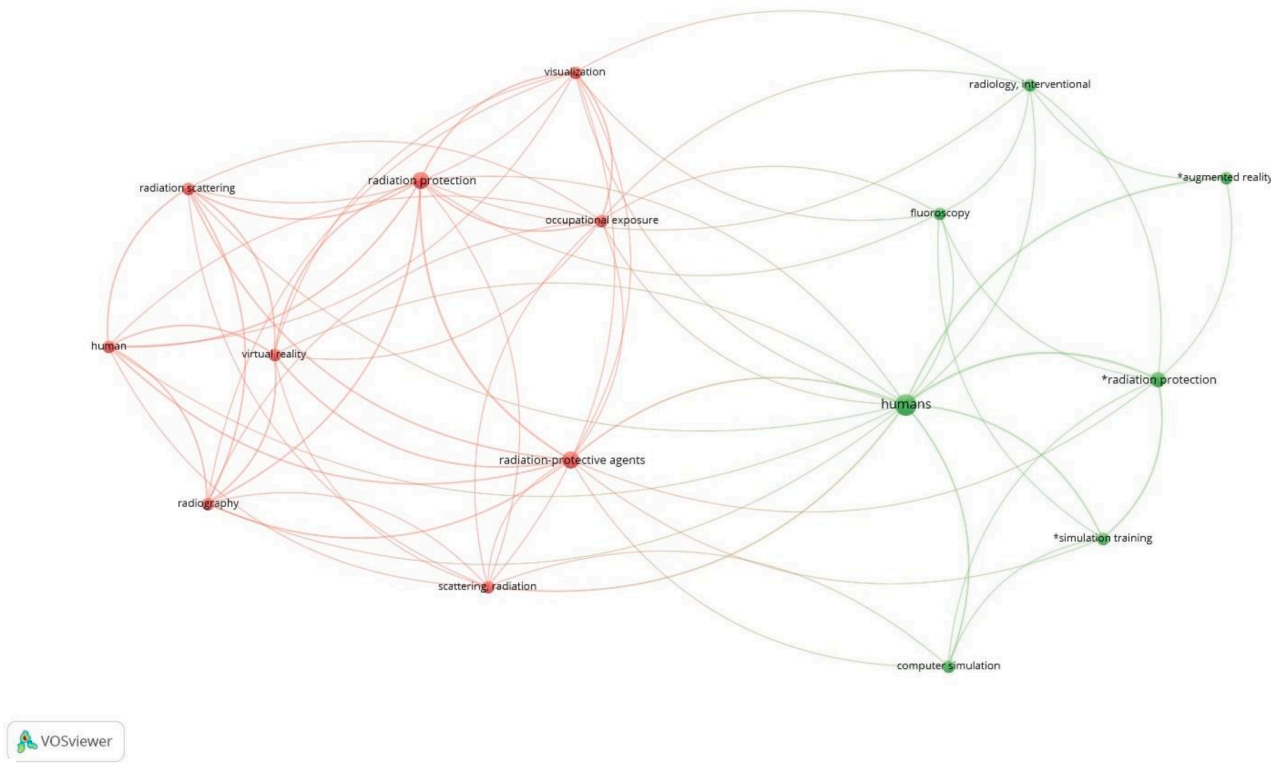
The author's collaboration included studies with scale time (adapted VOSviewer).



Note: A1-A9: studies included from databases; B1: studies included from snowballing; A1 - [5]; A2 - [4]; A3- [10]; A4 - [1]; A5 - [9]; A6- [8]; A7- [7]; A8- [6]; A9 - [2]; B1- [3]. larger balls - 2 publications included in this review (9 authors are grouped in dark blue and two are in the purple cluster)

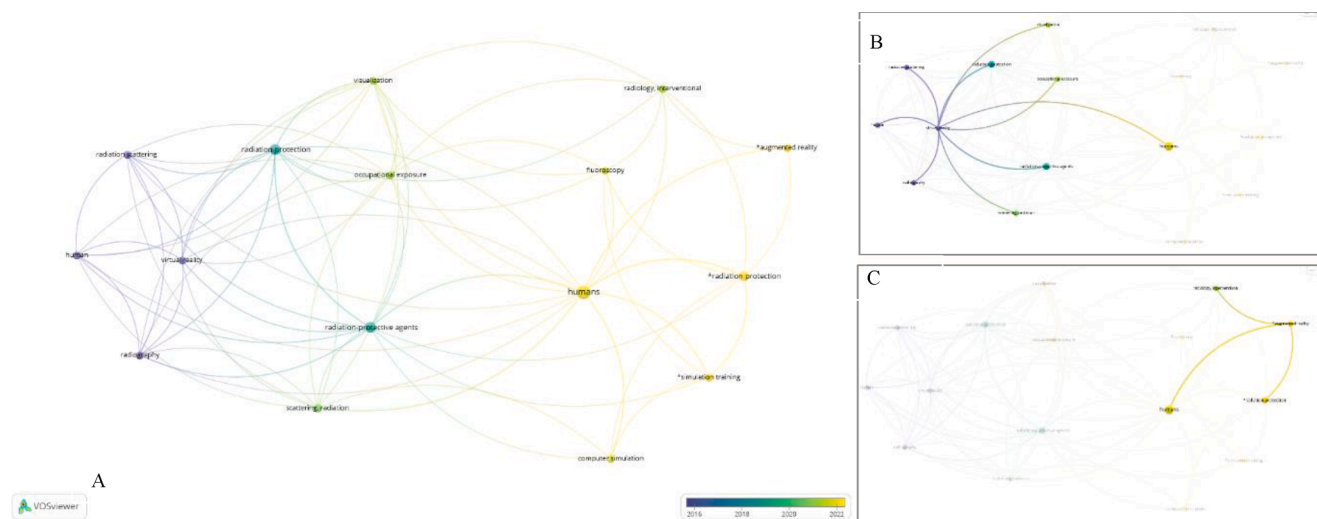
Appendix H

Keyword co-occurrence network map in red and green cluster (VOSviewer).



Appendix I

Dynamic keyword co-occurrence network map – general view (A); “virtual reality” co-occurrence network map (B); “augmented reality” co-occurrence network map (C).



Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.radi.2025.103179>.

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