Clinical Applications of Virtual Reality in Radiology: a Scoping Review

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Abstract

Background: Virtual reality (VR) and augmented reality (AR) have emerged as innovative tools in healthcare, offering new avenues for enhancing patient care and procedural outcomes. Their applications range from improving preoperative planning and pain management to providing advanced procedural support and training. Despite their growing integration into clinical practice, evidence on their cost-effectiveness and specific clinical benefits remains limited. This review aims to map the current landscape of VR and AR applications in medicine and highlight areas for future research.

Objective: This scoping review explores the clinical applications of virtual reality (VR) and augmented reality (AR) in the medical field, aiming to assess the target areas, cost-effectiveness, and benefits of these technologies.

Methods: We conducted a comprehensive literature search using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. A total of 15 primary studies were included, covering diverse populations and applications of VR and AR.

Results: In total, 15 studies (N?=?781 patients) were included, with sample sizes ranging from 6 to 120. These studies highlighted various clinical applications of VR and AR, including preoperative planning, pain management, and procedural support. Although several studies demonstrated improvements in patient experiences and diagnostic accuracy, cost-effectiveness data were lacking. Notably, 47% of the studies focused exclusively on pediatric populations (N?=?363), and 33% were randomized controlled trials. Quality assessment using the STARD criteria revealed that 60% of studies were rated as good (score >12), 27% as fair (score 10–12), and 13% as suboptimal (score <10), with inter-reader reliability showing substantial agreement (ICC?=?0.76; 95% CI: 0.64–0.91). Furthermore, individual studies demonstrated significant benefits of VR interventions; for instance, one study reported a reduction in distress scores by a mean of 3.0 (95% CI: 1.0–5.0) and a decreased need for parental presence (risk ratio 0.3; 95% CI: 0.1–0.7; p?<?0.001) compared to conventional methods.

Conclusions: Virtual reality and augmented reality technologies hold promise in enhancing patient care and procedural outcomes. Future research should focus on the cost-effectiveness of these technologies and identify specific target populations that would benefit the most. Additionally, adherence to the Standards for Reporting of Diagnostic Accuracy (STARD) guidelines should be encouraged to ensure transparent and comprehensive reporting in VR and AR studies.

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Conclusions: Virtual reality and augmented reality technologies hold promise in enhancing patient care and procedural outcomes. Future research should focus on the cost-effectiveness of these technologies and identify specific target populations that would benefit the most. Additionally,

adherence to the Standards for Reporting of Diagnostic Accuracy (STARD) guidelines should be encouraged to ensure transparent and comprehensive reporting in VR and AR studies.

Keywords: Virtual reality; augmented reality; scoping review; Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA); medical field; clinical applications

Introduction

Virtual reality (VR) and augmented reality (AR) are technological advancements extensively used in entertainment, sports, gaming, and simulation [1]. VR and AR hold the potential to revolutionize how clinicians manage healthcare conditions and how patients undergo diagnostic testing and therapeutic procedures. These technologies can assist healthcare professionals in addressing cognitive challenges related to patient treatment and planning, managing phobias, alleviating pain, addressing other disease-related symptoms, and planning complex virtual surgeries [2], thereby enabling more cost-effective decision-making in patient care.

VR is characterized by immersing the user in a simulation, specifically in a three-dimensional computer-generated environment [3]. Within this environment, users have no visualization of the world outside the virtual environment; sensory input is provided through a head-mounted display, replacing the user’s native surroundings. As a result, users perceive themselves as experiencing a non-physical virtual world [3, 4, 5]. In contrast, AR does not entirely eliminate the real world from the user’s view [4]. Instead, virtual objects and structures are superimposed onto the “real world” via a head-mounted display or another type of interface, enabling users to interact simultaneously with both real and virtual elements [6, 7].

Competitive markets and advances in hardware and software have driven down the costs of VR and AR technologies, facilitating their integration into various medical applications such as medical education, procedural planning, and therapeutic interventions.

Current and future applications of VR and AR include providing alternative approaches to 3D printing allowing radiologists to interact with images in a 3D format, aiding in a better informed decision-making process; (2) facilitating the understanding of anatomic relationships for diagnosis, interventional radiology procedures and surgical planning of complex health conditions; (3) assisting in real-time reconstructions (e.g. AR superimpositions onto patients during vascular interventions); (4) enhancing image interpretation in radiology reading rooms [8]]; (5) serving as relaxation or distraction therapy to reduce pain and anxiety in patients, particularly as an alternative to medication [3]; (6) offering interactive VR and AR simulations for education and training on challenging anatomical concepts [4]; (7) expediting review and analysis of imaging data for clinical research [9]; (8) enabling remote monitoring and treatment of patients [9].

Despite the availability of scoping and systematic reviews on medical education applications of VR and AR [10, 11, 12] and of papers on clinical applications of VR and AR in radiology on an unstructured or narrative basis [3, 4, 9, 13]; to our knowledge no previous scoping or systematic review has specifically addressed their clinical applications in the pediatric or adult population. Of note, the pediatric population can particularly benefit from these technologies due to behavioral challenges during imaging.

The purpose of this scoping review is to assess the current state of knowledge on noneducation-based applications of VR and AR in radiology in pediatric and adult populations. A comprehensive understanding of the current applicability of VR and AR in the medical field should guide further investigations into their value in specific areas of medicine, support the development of evidence-based guidelines, and highlight gaps in the literature concerning their use for both patients and healthcare professionals. Hence, the overarching study questions of this scoping review are:

1. What are the target areas of non-educational clinical applications of VR and AR in the pediatric and populations?
2. Are VR and AR cost-effective strategies in the clinical or surgical management of patients compared with traditional strategies?
3. What are the benefits of utilizing these novel technologies in the proposed population, including their impact on the accuracy of diagnostic tests?

Methods

The Research Ethics Board of our institution waived approval due to the public domain nature of the primary studies included in this review.

2.1 Study Design Framework

The Patient, Intervention, Comparison, and Outcome (PICO) framework and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [14] were used to define the study cohort characteristics, study design, and methods. PRISMA is not a quality assessment tool, but instead it is designed to ensure transparent reporting in systematic reviews. The Standards for Reporting of Diagnostic Accuracy (STARD) [15] were applied to assess the reporting quality of the literature included in this review.

2.2 Search and Data Collection Strategies

The initial electronic literature search was conducted by two independent reviewers (T.O. and H.B.) with the assistance of an experienced staff librarian (Q.M.) and was later updated by an independent reviewer (S.M.L.) with another staff librarian (J.C.). Studies were identified using a predefined list of search terms tailored for MEDLINE OvidSP (US National Library of Medicine, Bethesda MD), EMBASE (Elsevier, Amsterdam, The Netherlands), and the Cochrane Library from January 2000 to January 30, 2025. Manual screening of reference lists from the included studies was also conducted.

Search terms were adapted for each database's vocabulary, using combinations such as (virtual reality OR augmented reality) AND (diagnostic imaging OR radiology) AND (pediatrics OR infant OR child OR adolescent). Additional age-specific text search terms were applied. Details of the search strategy are available in Supplementary table 1.

2.3 Study Selection Process

Titles and abstracts were independently screened for inclusion by three reviewers (T.O., H.B., and S.M.L.) to determine eligibility. Full articles were read by reviewers for final inclusion. Disagreements were resolved by a senior reviewer (A.S.D.), an experienced epidemiologist and radiologist with over 20 years of expertise, who acted as a tiebreaker.

Papers with consensus among reviewers were included in the review. Following the resolution of discrepancies, full-text articles of the selected abstracts were retrieved. These articles were then assessed using predetermined eligibility criteria. The initial batch was reviewed by T.O. and H.B., while the updated batch was reviewed by S.M.L., with calibration sessions involving A.S.D. for systematic consistency. Details of the selection process are illustrated in Fig. 1.

2.4 Eligibility Criteria for Primary Studies

Studies were included if they met the following criteria: (a) clinical studies or case series with 6 or more subjects: (b) use of virtual reality as a clinical (e.g., pre-operative planning), interventional (e.g., as an analgesic or relaxation method, ultrasound-guided anesthesia), alternative therapy (e.g., as an alternative to 3D printing in radiology) or training tool to an imaging diagnostic test or imaging-guided procedure or that used imaging as an outcome measure; (c) be written in English, Spanish, Portuguese, French, German, Korean, or Italian; (e) be PubMed-indexed.

Exclusion criteria included non-human studies, publications prior to 2000 (to focus on newer technologies), abstracts from scientific meetings, editorials, personal opinions, letters to the editor, protocols, case reports, and reviews.

2.5 Data Extraction, Analysis and Critical Appraisal

Following the final selection, data extraction and critical appraisal were performed. The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) checklist [9] was used to guide the database of study characteristics for the included studies.

The Standards for Reporting of Diagnostic Accuracy (STARD) checklist [15] was used to assess reporting quality and methodology of selected primary papers. The original 2015 STARD [15] has a 34-point maximum for the sum of the 30 items, (all articles receiving a score of 1) taking into account that items 10, 12, 13 and 21 are dichotomous (i.e. a, b for each item) and items 10b, 11, 12a/b, 13a/b; 14–17; 22; 23, 24, 25 related to a reference standard which was not used in most primary studies of this review, a modified maximum score of 20 was used to assess reporting quality of included primary articles. Scores were categorized as follows: (a) good quality: >12; (b) fair quality: 10–12; (c) suboptimal quality: <10. The papers were independently assessed, reviewed and scored by the reviewers (T.O. and H.B). Any discrepancies in scoring, where consensus was not achieved, was discussed and resolved by the tiebreaker (A.S.D.).

2.6 Statistical Analysis

STARD scoring was designated as follows: 1, fully meets condition; 0.5, partially meets condition; 0, does not meet condition; N/A, not applicable. STARD scores were categorized as follows: (a) good quality: >12; (b) fair quality: 10–12; (c) suboptimal quality: <10.

STARD agreement levels were defined as: total agreement, identical scores by both reviewers; partial agreement, scores differed by 0.5 points (e.g., 0 and 0.5); no agreement, full score difference (e.g., 0 and 1). Inter-rater reliability was assessed using intraclass correlation coefficients (ICCs) to evaluate agreement between reviewers' STARD scores [16]. As per Altman et al [16] based on 95% confidence intervals of ICCs, values > 0.80 indicated excellent inter-reader reliability; values 0.61-0.80, substantial reliability; values 0.41-0.60, moderate reliability and values ≤0.40, poor reliability.

Results

3.1 Study Selection

The search yielded 1,120 references, from which 986 duplicates and disparate studies were removed. A total of 134 studies underwent title and abstract screening. Of these, 103 were excluded for not meeting the inclusion criteria. Subsequently, 31 studies were assessed for full-text eligibility, and 18 were excluded as described in Figure 1. Ultimately, 15 studies were included in the scoping review: 9 (60%) focused on pre-operative planning and 6 (40%) on interventions. The 15 included primary studies encompassed a total of 781 patients. However, due to the lack of standardized reporting of demographic details, a comprehensive age analysis was not feasible. Average, median, or range for age of patients of included primary studies were reported in this review as they appeared in the original articles.

The summary characteristics of the primary studies and participants are presented in Table 1.

3.2 Primary Studies' Research Design

Most primary studies (33%) were randomized controlled trials (RCTs). Sample sizes across all studies were small (ranging from 6 to 120 patients). Furthermore, psychometric properties [17] [Asunta 2019] were not applied to measurements or scales used in these studies.

Table 1 summarizes the research designs and patient characteristics:

- Randomized controlled trials (RCTs): 5 studies (33%) [18, 19, 20, 21], including one single-blinded study [22].
- Descriptive/case series: 4 studies (27%) [22, 23, 24, 25].
- Protocol development/case series: 2 studies (13%) [26, 27]. -Prospective cohort study: 2 study (13%) [28, 29].
- Cross-sectional study with a control group: 2 study (13%) [30, 31].

  There was substantial variability in study design, power calculations, and sample sizes across studies. The greatest variability was observed within case series, with sample sizes ranging from 6 patients in studies by Souzaki and Ieiri [25, 28] to 120 participants in Ryu's paper [30].

Seven of the 15 studies (47%) focused exclusively on pediatric populations (N = 363 patients), including studies by Han et al., Ryu et al., Souzaki et al., Stunden et al., Ieiri et al., Milano et al., Zhao et al., [20, 21, 25, 26, 28, 29, 31]. Patient ages ranged from 0.1 month to 15 years. However, demographic reporting was inconsistent, with some studies failing to mention patient sex [24, 25, 28, 29, 32].

3.3 Reporting Quality of Primary Studies (using STARD)

The overall quality of reporting, as assessed using the STARD guidelines [10], was deemed fair. Of the studies included in this review 60% were considered as presenting with good quality (scores >12) [19, 20, 21, 22, 26, 27, 31, 32], 27% were considered as of fair quality (scores ≥10 and ≤12) [18, 23, 28, 29] [and 13% were classified as presenting with suboptimal quality (scores <10) [24, 25]

Several sections of the primary studies were suboptimally reported, including intended sample size, flow diagrams, registration information, and full protocol access. Suboptimally reported sections included:

- **Title or Abstract and Introduction: item 1:** identification of the study as a diagnostic accuracy study using at least one measure of accuracy: no papers met this criterion.
- **Methods (Study Design, Participants, Test Methods, Analysis): item 6:** eligibility criteria: 4/15 studies scored 0; **item 8:** reporting where and when eligible participants were identified: 3/15 scored 0, and 2/15 scored 0.5; **item 9:** participant recruitment methods (e.g., consecutive, random, convenience): only 8/15 (53.3%) studies provided details; **item 18:** intended sample size and determination method: only 5/15 (33.3%) studies provided this

information.

- **Results (Participants, Tests): item 19:** flow diagrams of participant selection: only 6/15 studies (40%) included diagrams; **item 20:** 10/15 (66.6%) scored 1, 2/15 (13.3%) scored 0.5 for demographic and clinical characteristics.
- **Discussion: item 26:** 2/15 (13.3%) papers scored zero on consensus for not adequately presenting study limitations.
- **Other Information: item 28:** 7/15 (46.7%) did not present a registration number or the name of a registry. This may be because only 5 papers (33%) were classified as clinical studies; **item 29:** only 4/15 (26.7%) studies mentioned where the full protocol could be accessed; **item 30:** 5/15 papers (33.3%) did not list sources of funding or other forms of support.

3.4 Inter-reader Reliability of STARD Scoring

Inter-reader agreement for STARD scoring was substantial, with an ICC of 0.76 (95% CI: 0.64–0.91) for the 15 reviewed studies.

Summary of Evidence

This scoping review aimed to address the following overarching questions:

3.5.1 Target areas of clinical applications of VR and AR in the pediatric population:

Clinical applications of VR and AR reported in the primary studies primarily related to pre-surgical planning. Milano et al. [29] explored the advantages of enhanced 3D visualization for complex cardiac surgery planning, while Kockro et al. [23] tested new intraoperative software. Qui et al. [30] assessed the effectiveness of image processing in pre-surgical planning. Zhao et al. [31] and Simpfendorfer et al. [18] reported on the intraoperative support provided by VR. As direct clinical interventions, VR was compared to conventional therapies in studies by Yang et al. and Nambi et al. [22, 32]. In more recent investigations, Chuan et al. [19] designed a high-fidelity VR trainer for teaching ultrasound-guided regional anesthesia skills, whereas Han et al. [20] and Ryu et al. [21] each showed that immersive VR education can reduce pediatric anxiety and procedural times during chest radiography. Sadri et al. [27] further demonstrated the potential of AR overlays to reduce contrast use during cerebral embolic protection in TAVR without prolonging the procedure.

3.5.2 Cost-effectiveness of VR and AR in clinical or surgical management of patients compared conventional strategies

Sadri et al. [27] examined the cost-effectiveness and procedural improvements offered by AR during cerebral embolic protection (CEP) in transcatheter aortic valve replacement (TAVR). The study demonstrated that AR significantly reduced the need for contrast angiography during procedures, resulting in lower contrast volume usage without increasing procedure times. The reduction in contrast use also minimized the risks of contrast-induced complications, such as nephropathy, providing additional long-term health benefits. The authors emphasized that while AR systems may involve substantial initial investment, the reduction in contrast usage, procedure times, and improved physician confidence make AR a cost-effective solution in procedural interventions.

Otherwise, none of the remaining primary studies of this review specifically demonstrated the cost-effectiveness of VR or AR in clinical applications. However, certain operating systems, such as the Virtual Intracranial Visualization and Navigation (VIVIAN) System used in Kockro et al.'s study

[23]. were associated with high costs due to specialized equipment and programming. Conversely, Yang et al.'s study [22] utilized commercially available head-mounted displays (HTC VIVE), which are head-mounted hardware and software displays/systems. These systems have become increasingly less expensive since the time of the study's publication, potentially enhancing their accessibility for broader clinical use.

3.5.3 Benefits of using VR and AR, including implementation of the accuracy of diagnostic tests

Nambi et al. stated that "virtual reality training is widely used because it reduces the difficulty of rehabilitation and increases participant safety" [32]. Yang et al.'s study reported significant improvements in APAIS (Amsterdam Preoperative Anxiety and Information Scale) scores for assessing preoperative anxiety in the VR group compared to the control group [22]. Furthermore, studies by Ieiri, Souzaki, and Milano [25, 28, 29] demonstrated the benefits of VR-assisted surgical planning. Their findings highlighted accurate identification, successful imaging guidance, and precise resection planning facilitated by VR.

The VR studies described in the primary papers of this review encompassed diverse applications, ranging from clinical interventions aimed at improving patient care to educational programs for training and skill development. Similarly, AR studies revealed versatile applications, with a strong focus on enhancing clinical procedures and providing educational guidance across various medical and surgical contexts. This was compared to conventional training exercises combined with Swiss ball rehabilitation over a four-week period. Zhao et al. [31] evaluated MR virtual endoscopy (MRVE), a virtual imaging technology that enables the visualization of the inner surface of lumina. MRVE was used to identify pathological changes in the cerebral ventricles and measure lumen diameters in hydrocephalus patients. Simpfendorfer et al. [18] employed intraoperative cone-beam CT images with AR guidance to ensure safe resection lines in laparoscopic partial nephrectomy procedures. Yang et al. [22] introduced a preoperative VR experience using 3D-reconstructed knee MRIs for patients undergoing arthroscopic knee surgery. This intervention reduced preoperative anxiety and improved patient satisfaction, underscoring the clinical utility of VR in enhancing the preoperative care experience.

Nambi et al. [32] implemented balance exercise training using the ProKin system, focusing on core stability in university football players with chronic low back pain. Beyond these examples, Chuan et al. [19] developed a high-fidelity VR trainer for ultrasound-guided regional anesthesia (UGRA), demonstrating improved skill acquisition among novice practitioners and reinforcing VR's potential to enhance procedural accuracy and confidence. Han et al. [20] and Ryu et al. [21] similarly showed that immersive VR education decreases anxiety and distress in pediatric patients undergoing chest radiography, thereby reducing procedure time and potentially improving the quality of imaging. Meanwhile, Sadri et al. [27] highlighted how AR overlays can offer precise visualization of patient-specific anatomy in TAVR procedures, minimizing contrast usage without increasing procedure time. Collectively, these findings underscore the significant benefits of VR and AR in achieving more accurate diagnostics, improved safety, and higher procedural efficiency.

Discussion

4.1 Summary of Evidence

This scoping review identified published literature on the use of VR and AR as clinical or surgical imaging based-aid tools, for both pediatric and adults populations. Several studies highlighted the potential of these immersive technologies to enhance surgical planning, reduce patient anxiety, and improve procedural efficiency.

4.2 Population

Different types of treatments applied virtual reality experiences. Hohlweg-Majert et al. in Navigational Maxillofacial Surgery Employing Virtual Models [24] assessed the benefit of using VR in patients ranging from 3 weeks to 80 years. This article specifically informed readers on how virtual reality reacts in a preoperative environment and as an intraoperative navigational tool. Most of our research had no intention of restricting themselves to specific populations or age categories since we wanted to learn about the benefits of using this unique technology. Because we only found fifteen papers that addressed the research questions of this scoring system, we concluded that VR and AR are at critical stages of evaluation compared to existing technologies. Many factors to consider when identifying target audiences, evaluating outcomes such as patient health and clinician benefits, and assessing the feasibility and resources for translation and implementation into clinical practice. As a result, we felt it was critical not to limit our target group, and we thought it was necessary to consider the total influence of VR and AR on all populations.

4.3 Improvement of Population Health and Experiences of Care

Our scoping study assessed new services that are now available due to advances in virtual reality technology, which may help all physicians to deal with complex surgeries. VR can facilitate the conduct of procedures for distal radius fractures which are typically challenging. VR/AR allows the surgeon to do a more effective procedure because it affords a better view of the distal radius, which has a small diameter. The use of virtual reality increased the surgeon's anatomic prediction capability as anticipating the final placement of the distal radius post osteotomy favoured the use of a CT virtual reality environment. The improved patient experience in alleviating pain and anxiety in procedures is demonstrated. It will be important in the future to create more objective criteria guidelines concerning patients' experiences during VT/AR procedures for different age groups, including patients for whom VR can be challenging to tolerate such as older patients and persons with phobias. Additionally, VR has been shown to alleviate pain or anxiety, an effect that Han et al. [20] and Ryu et al. [21] both demonstrated in pediatric patients undergoing radiographic exams. By immersing children in a virtual environment before or during a procedure, these studies reported less distress, shorter procedure times, and higher patient (and parental) satisfaction.

From a training standpoint, Chuan et al. [19] showed that novice anesthesiologists learning ultrasound-guided regional anesthesia via VR-based training could achieve more accurate skill acquisition and improved procedural confidence. Collectively, these examples suggest that VR or AR can improve health outcomes and care experiences by fostering higher provider proficiency and supporting patients—whether by lowering anxiety in children or boosting operator skill in complex tasks. However, future research should establish objective guidelines on how VR/AR influences patient and provider experiences, with attention to populations (e.g., older adults, patients with phobias) who might find immersive technologies more challenging.

Based on the target areas of clinical applications of VR/AR of this review the information from primary studies focused more on the benefit of VR utilization was from the physician's perspective as they would be able to better understand the 3D reconstructed MR images.

Yang et al [25] noticed VR experience in 3D reconstructed magnetic resonance images on anxious patients undergoing arthroscopic knee surgery. Because most adults realize the realities of undergoing surgery, this form of virtual reality usage would be more acceptable as a pediatric intervention. Nambi et al [32] observed a study in which the age range was 18-25 years old and determined the radiological and biochemical effects of VR training in football players with persistent back pain. This is an example of proper VR use in a young-adult population, where VR is used to meet the needs of this specific population. Finally, Qui et al [30] examines the potential clinical applications of presurgical 3D environments in patients with brain gliomas near motor circuits. The participants in this study ranged from 4 to 70 years old. The average age, however, was 46 (+/- 17.98). This study is an excellent example of VR being used in people who have more severe acquired health consequences due to simply living longer. Therefore, our broad target group enabled us to examine the benefits of this unique technique across all specified demographics. However, future studies must define whether VR would be more effective for specific populations.

4.4 VR Technology

Few research papers suggested whether or not VR was a cost-effective intervention choice during our scoping analysis. For example, the VR technology utilized in Kockro [23] was VIVIAN (Virtual Intracranial Visualization and Navigation). The VIVIAN system enables users to interact with complex imaging data rapidly, complete, and intuitive; nevertheless, when discussing the VIVIAN system's cost, the study revealed that it was a costly operating system. Milano et al.'s study [29] also mentioned need for cost-effect evaluation in the future, but deemed VR costs to be lower than 3D printing in pre-surgical planning. All the other studies made no mention of how VR affects expenses or how the VR system can help to lower intervention costs. As a result, given that the bulk of the studies we discovered focused on VR intervention, we propose that future research and development should concentrate on the cost of VR. For example, VR and AR anxiety reduction equipment, or cost-effective presurgical technology that can replace existing high-maintenance equipment, are intriguing research avenues to study.

4.5 Standards for Reporting Diagnostic Accuracy (STARD) of Primary Studies

Our review found modest compliance with the STARD checklist, with only 19/34 (56%) of checklist sub-items being reported across studies. Since most primary papers did not follow traditional randomized controlled trial designs or include a reference standard for estimation of diagnostic accuracy indexes, most studies lacked reference standards in their design, precluding the assessment of STARD sub-items related to a reference standard (test methods: 10b, 11, 12a/b, 13a/b; analysis: 14–17; results (participants): 21b; 22; results (test results): 23, 24, 25) which were deemed inapplicable to the analysis of the data of primary studies of this review.

Additionally, many studies failed to report variability between VR and non-VR groups (item 17) or adverse events (item 25). These gaps highlight challenges in identifying biases and ensuring transparency in research reporting. Improved adherence to STARD guidelines is necessary to reduce bias and enhance replicability and peer approval of future studies.

Limitations

Our scoping review has limitations. We included only studies published in English, Spanish, Portuguese, French, German, Korean, or Italian, which may have introduced publication bias. Additionally, the definitions of VR and AR are evolving and may differ among research groups. The primary studies of this review encompassed a wide age range but lacked sufficient focus on pediatric populations. While we intentionally included both children and adults to provide a comprehensive overview, age-specific factors may influence outcomes. Future research should conduct age-stratified analyses to provide more tailored insights. The need for more pediatric-focused studies is particularly evident, given the high potential for clinical benefit in this population.

Some of the included studies lacked rigorous research designs, such as reference standards for assessment of diagnostic test accuracy, limiting the assessment of STARD items. Furthermore, the restricted sample sizes and case series' characteristics of many of the included studies reduced the reliability and external validity of conclusions. The considerable variability in statistical methodologies also hindered result aggregation. Approximately 40% of studies exhibited fair or suboptimal reporting quality, highlighting the need for more robust research design in future studies. The shift from case series and personal experiences toward robust clinical trials with rigorous methodology is vital for advancing the field.

Conclusion

Despite the methodological limitations of this scoping review, our findings suggest that VR holds significant potential to improve medical care. VR enhances imaging quality compared to traditional tools and offers benefits such as reduced preoperative anxiety and improved surgical outcomes. However, insufficient data exist to confirm VR's cost-effectiveness, STARD guidelines should be more consistently followed to enhance the methodological quality of future studies, and the identification of target populations remains an area for further scientific exploration. Future clinical trials investigating new indications for VR/AR use to address gaps in the current literature and evaluating the cost-effectiveness of VR compared to other imaging and sedation techniques, particularly in vulnerable populations, such as children and older adults, are key for the advancement of the field.

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Figure legends

Fig. 1. Literature search output and study identification.

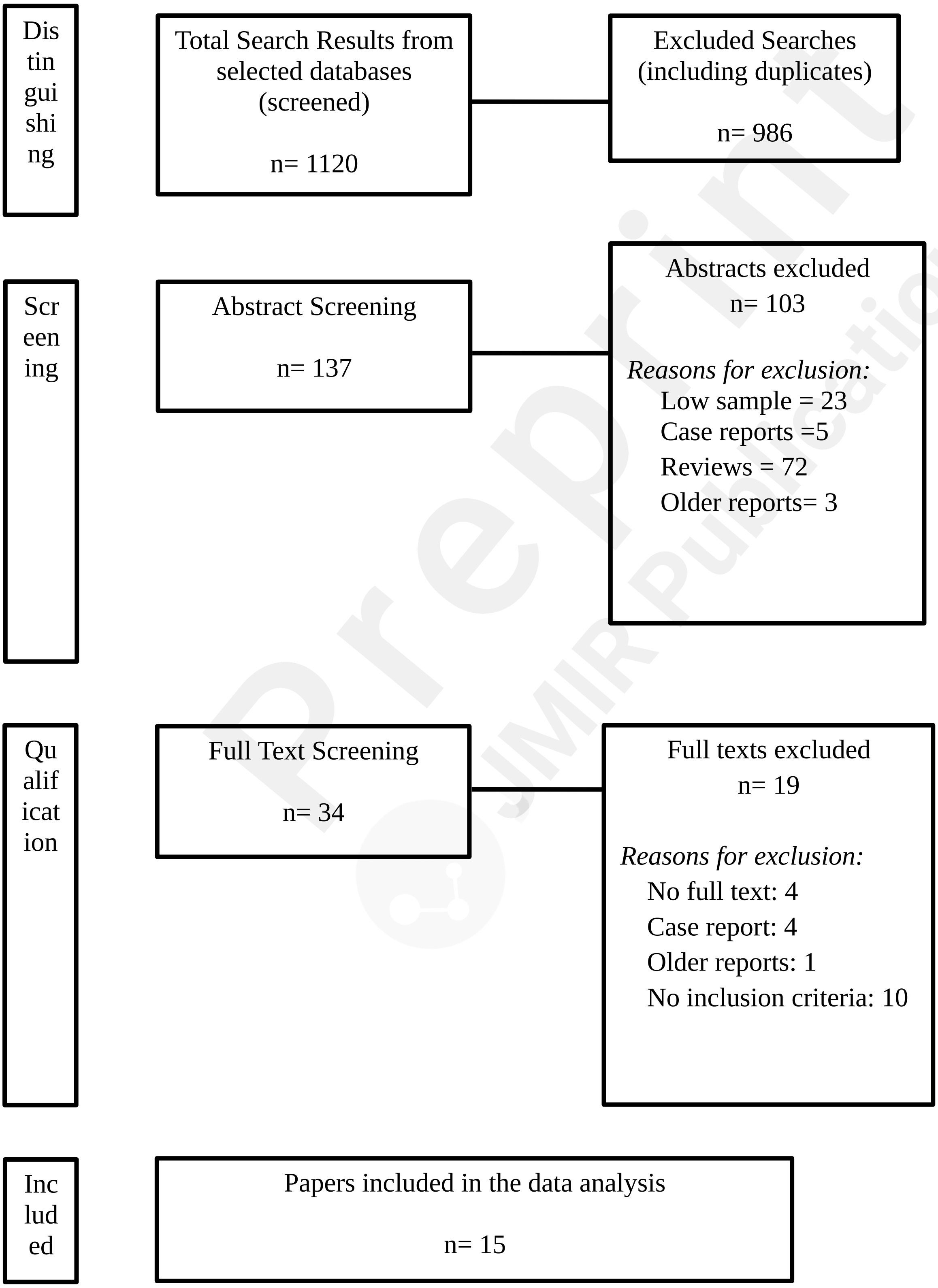


Table 1–A: Baseline demographic data, study year, study design, and key findings of the selected primary papers of this review.
Pediatric Only *; Adult Only **

First Author	Year of Publication	Country of Origin	Number of patients	Mean Age (SD) Years)	Median age (range) Years	% of Male (rounded)	Prospective vs Retrospective Design	Field	Diagnosis	Key Findings
Kockro, R.A. [23]	2000	Singapore	21	n/a	n/a (11-66)	48%	Retrospective	Neurosurgery	Intracranial pathology: complex neurosurgical anatomy of intra- and extra-axial brain tumors and vascular malformations.	The VIVIAN system allows users to work with complex imaging data in a fast, comprehensive, and intuitive manner but still requires a costly operating system. VIVIAN system substantially contributed to surgical planning by 1) providing a quick and better understanding of intracranial anatomic and abnormal spatial relationships, 2) simulating the craniotomy and the required cranial base bone work, and 3) simulating

										intraoperative views.
Hohlweg-Majert, B. [24]	2005	Germany	107	n/a	n/a (0.1-80)* *0.1 year = 3 weeks	n/a	Prospective	Craniofacial	Craniomaxillofacial malformation	Author's opinion-based without data analysis: Image-guided treatment improves preoperative planning by visualizing the individual anatomy and outlining the intended reconstructive outcome. Intraoperative navigation makes tumor and reconstructive surgery more reliable by showing safety margins, saving vital structures, and leading the reconstruction to preoperatively planned objectives.
Qiu, T.M. [30]	2010	China	45 (baseline); 40 (follow-up)	46.0 (17.98)	n/a (4-70)	58%	Prospective	Neurosurgery	Cerebral Glioma	VR-based 3D stereoscopic tractography visualization enhances understanding of anatomic information of intra-axial tumor contours and adjacent PT, results in surgical trajectory optimization initially, and maximal safe tumor resection finally. Surgeons can predict the long-term motor

										functional outcome based on EPT increasing amplitude.
* Ieiri, S. [28]	2012	Japan	6	n/a	n/a (6-15)	n/a	Prospective	Hematology	Hematological disorders: hereditary spherocytosis (HS) and idiopathic thrombocytopenia purpura (ITP) - treated by laparoscopic splenectomy with one patient also requiring a laparoscopic cholecystectomy	The proposed navigation system provides real-time anatomical information that cannot be obtained without the system. Registration accuracies for the study cases were acceptable in clinical operation settings.

*Souzaki, R. [25]	2013	Japan	6	n/a	n/a (1-12)	n/a	Prospective	Oncology	Pediatric malignancy (abdominothoracic)	The proposed AR navigation system was useful for detecting the tumor location during pediatric endoscopic surgery.
*Zhao, C. [31]	2015	China	30	n/a	n/ (0.1-1.7)* *1-20 Months	47%	Prospective	Neurosurgery	Hydrocephalus/ Intracranial pathology: clinical manifestation of enlarged head circumference, increased intracranial and growth retardation	"MR virtual endoscopy provides a non-invasive diagnostic modality that can be used as a supplemental approach to ventriculoscopy. Requires future studies to assess sensitivity and specificity of the technique."
**Simpfendorfer, T. [18]	2016	Germany	10	n/a	n/a (38-69)	70%	Prospective	Urology	Renal malignancy (with complex or endophyti	Use of CBCT is feasible, safe and allows for direct acesss to complex or endophytic renal masses.

									c tumor localization)	
Yang, J.H. [22]	2019	South Korea	48	n/a	n/a Group VR: (15-62); Group Non-VR (20-65).	0 (all females)	Prospective	Orthopedics	Knee Pathology: Ligament rupture, Meniscus tear, Chondral lesion	Positive effects of VR experience of 3D reconstructed knee MRIs in patients undergoing arthroscopic knee surgery reducing anxiety around surgical encounters.
*Han, S-H [20]	2019	Korea	99 in total Virtual reality group: 49; usual care group: 50	VR group: Mean 5.8 (1.3 years); Control group: Mean 5.6 SD, 1.2)	4-8 years	VR group: boys: 32 (65.3%); control group: boys: 26 (52.0%)	Prospective	Radiology	Training of experimental group with a 3-minute immersive virtual reality experience of the process of chest radiography guided by	During chest radiography, distress scores were lower in the treatment group, with a mean difference of 3.0 (95% CI 1.0 to 5.0). Compared with the control group, the virtual reality group had fewer children classified as distressed (score _5) (risk ratio 0.3, 95% CI 0.1 to 0.7), less need for parent presence (risk ratio 0.3, 95% CI 0.1 to 0.9), higher parental satisfaction scores (MD 20.8, 95% CI 21.5

									animation and narration.	to 20.1) and reduced procedure time (MD 19.9 seconds, 95% CI 6.6 to 33.3).
**Nambi, G. [32]	2020	Saudi Arabia	36	n/a	n/a (18-25)	n/a	Prospective	**Physiatry**	Chronic low back pain	Positive effects of VR training on imaging and biochemical aspects of study subjects.
*Milano, E.G. [29]	2021	UK	10	n/a	n/a (0-1.1)* *0.1-13 months	n/a	Retrospective	Cardiology	DORV and complex interventricular communications	3D pdf this reached only 70%, whereas it was 95% after VR. Virtual reality can enhance understanding of suitability for biventricular repair in patients with complex DORV if compared to cross-sectional images and other 3D modelling techniques.
*Stunden, C. [26]	2021	Canada	92	n/a	n/a (4-13)	61%	Prospective	Anesthesiology	examines the effectiveness of virtual reality (VR) simulation training in ultrasound-guided regional anesthesia.	VR-based simulation significantly improves clinical performance in ultrasound-guided regional anesthesia compared to standard training methods.

*Ryu, J-H [21]	2021	Korea	120 in total Virtual reality group: 60 tablet video group: 60		VR group: Mean 6.0 (4.8-7.0 years); tablet video group: Mean 6.9 (5.0-7.3)	VR group : boys: 25 (41.7 %) ; tablet video group : boys: 32 (53.3 %)	Prospective	Radiology	Evaluated the effect of VR, compared with standard video, on reducing anxiety and distress in pediatric patients undergoing chest radiography.	<u>The number of less distressed children (OSBD score < 5) was significantly higher in the VR group than in the tablet group (49 [81.7%]) vs. 32 [53.3%]) (p = 0.001). The OSBD scores, the need for parental presence, the procedure time, and the number of repeated procedures were all lower in the VR group.</u>
**Sadri, S. [27]	2023	United States	24	n/a	AR guidance group: 84 (79-87), control group: 75(73-85)	AR guidance group : 7 (58%), control group : 8 (66.7	Prospective	Anesthesiology	evaluating the effectiveness of training methods. Specifically, the training of clinicians	VR-based simulation training is as effective as standard training methods, showing no significant difference in the clinical performance outcomes between the two groups.

						%)			in performing ultrasound-guided regional anesthesia, assessing whether virtual reality (VR)-based simulation can improve their skills compared to traditional training methods.	
**Chuan A [19]	2023	Australia, U.K.	21 novice and 15 experienced	Novice: Mean 21 (SD,		Novice: Males 7 (33.3	Prospective	Radiology	Training of an interventional procedure	The virtual reality trainer was comparable in terms of performance to other high-fidelity virtual reality softwares, possibility to act

			participants	1) Experienced: Mean 41 (SD, 6)		%); Experienced: 10 (66.7%)			using ultrasound-guidance	and quality of interface subscales (all p > 0.06),but not in the possibility to examine and self-performance subscales (all p < 0.009). It created workloads similar to those reported in real-life procedural medicine (p = 0.53).

Table 1–B: Information about number of timepoints, imaging modality, comparators, key findings, measurements, and hardware and software used in the virtual reality instrumentation of the selected primary studies of this review.

First Author	Year of Publication	Number of Timepoints	Imaging Modality	Comparators	Key Findings	Measurements	Hardware	Software	Pre-surgical or Intervention

Kockro R, A. [23]	2000	Single	MRI (Siemens Expert 1.0-T unit, Stuttgart, Germany; General Electric Signa 1.5-T unit, Milwaukee, WI), MRA, MRV venography, CT imaging (GE scanner; Picker 2000 scanner, Picker, Cleveland, OH)	n/a	The VIVIAN system allows users to work with complex imaging data in a fast, comprehensive, and intuitive manner but still requires a costly operating system. VIVIAN system substantially contributed to surgical planning by 1) providing a quick and better understanding of intracranial	Descriptive analysis: A report was written about each planning session. Each report was divided into two parts. One part recorded the size of the data set, the time needed for fusion and segmentation, the average system performance in frames per second, and the planning and simulation tools used during the session.	Descriptive analysis: A report was written about each planning session. Each report was divided into two parts. One part recorded the size of the data set, the time needed for fusion and segmentation, the average system performance in frames per second, and the planning and simulation tools used during the session.	VIVIAN (Virtual Intracranial Visualization and Navigation)	Pre-surgical

					anatomic and abnormal spatial relationships, 2) simulating the craniotomy and the required cranial base bone work, and 3) simulating intraoperative views.				
Hohlweg-Majert, B. [24]	2005	Dual (Baseline, pre-surgery and post-surgery as clinically indicated	Spiral-CT Contrast-enhanced MRI	n/a	Author's opinion-based without data analysis: Image-guided treatment improves preoperative planning by visualizing the individual	Pre- and postoperative spiral CT/MRI changes between the preceding and actual CT/MRI (e.g. assessment of pre- and post-operative periorbital deformation, optic nerve	Pre- and postoperative spiral CT/MRI changes between the preceding and actual CT/MRI (e.g. assessment of pre- and post-operative periorbital deformation,	VR surgical navigation tool (Stryker-Leibinger, Germany)	Pre-surgical

					anatomy, and outlining the intended reconstructive outcome. Intraoperative navigation makes tumor and reconstructive surgery more reliable by showing safety margins, saving vital structures, and leading the reconstruction to preoperatively planned objectives.	decompression).	optic nerve decompression).		
Qiu TM [30]	2010	Dual (Baseline and after 6 months)	3.0-T whole-body MRI (General	n/a	VR-based 3D stereoscopic tractography visualization enhances	Karnofsky Performance Scale (KPS): grading functional status	Karnofsky Performance Scale (KPS): grading functional	VR system (Dextroscope, Volume Interactions Pte. Ltd) -	Pre-surgical

			Electric Medical Systems, GE Signa VH/i) Diffusion tensor imaging (DTI), T1-weighted 3-D fast spoiled gradient-recalled		understanding of anatomic information of intra-axial tumor contours and adjacent PT, results in surgical trajectory optimization initially, and maximal safe tumor resection finally. Surgeons can predict the long-term motor functional outcome based on EPT increasing amplitude.	at 6-month evaluation Patient questionnaire (at follow-up)	status at 6-month evaluation Patient questionnaire (at follow-up)	the Fiber Tracking module of the VR system Volume-One 1.72 (VOLUME-ONE developers group) dTV. II (Image Process and Analysis Laboratory,	
Ieiri S	2012	Single	Multi-	n/a	The	Mean +/- SD of	Mean +/- SD of	3D viewer	Intervention

[28]			detector low CT (MDCT) (Aquilion 64, Toshiba Medical Co. Ltd.Tokyo, Japan)		proposed navigation system provides real-time anatomical information that cannot be obtained without the system. Registration accuracies for the study cases were acceptable in clinical operation settings.	fiducial registration error (FRE) and target registration error (TRE) between the lists of markers identified in the CT images for evaluation of registration accuracy	fiducial registration error (FRE) and target registration error (TRE) between the lists of markers identified in the CT images for evaluation of registration accuracy	software (Virtual Place 300, AZE Co Ltd., Tokyo, Japan	
Souzaki R [25]	2013	Single	MDCT (multi-detector computed tomography)	n/a	The proposed AR navigation system was useful for detecting the tumor	Descriptive report of success or not of tumor resection using the AR navigation	Descriptive report of success or not of tumor resection using the AR navigation	3D viewer software program (Virtual Place 300, AZE Co Ltd.,	Pre-surgical

			MRI		location during pediatric endoscopic surgery.				
Zhao C [31]	2015	Single	MRI (3D-T1 weighted, FSPGR; Signa EXCTTE 1.5 T MR machines (GE, USA),processing software (ADW 4.3) CT ventriculography [OPTIMN CT660 (128T) machine (GE,	Ventriculoscopy or CT imaging reference standard)	"MR virtual endoscopy provides a non-invasive diagnostic modality that can be used as a supplemental approach to ventriculoscopy. Requires future studies to assess sensitivity and specificity of the technique."	Descriptive characteristics and degree of obstruction of parts of the ventricular system (complete vs non-complete obstruction) by MRVE and ventriculoscopy	Descriptive characteristics and degree of obstruction of parts of the ventricular system (complete vs non-complete obstruction) by MRVE and ventriculoscopy	Processing software (ADW 4.3) for Signa EXCTTE Smooth imaging Navigator software	Intervention

			USA)]							
Simpfendorfer T [18]	2016	Single	CB-CT and fluoroscopy infusion	Nephrometry scores of tumors	Use of CBCT is feasible, safe and allows for direct acesss to complex or endophytic renal masses.	Descriptive feasibility and performance assessed by histopathological results, peri- and postoperative data.	Descriptive feasibility and performance assessed by histopathological results, peri- and postoperative data.	Open-source Medical Imaging Interaction Toolkit (MITK) syngo iPilot; Siemens Health-care,	Intervention
Yang, JH [22]	2019	Single	MRI	n/a	Positive effects of VR experience of 3D reconstructed knee MRIs in patients undergoing arthroscopic knee surgery reducing anxiety around surgical encounters.	Primary: Amsterdam Preoperative Anxiety and Information Scale score to measure level of anxiety Secondary: visual analog scale (VAS) scores measuring patient pain, preparedness, satisfaction, and stress	Primary: Amsterdam Preoperative Anxiety and Information Scale score to measure level of anxiety Secondary: visual analog scale (VAS) scores measuring patient pain, preparedness, satisfaction, and stress	Software 3D Slicer 4.6.2 (Brigham and Women's Hospital and The Slicer Community Autodesk 3ds Max (Autodesk ZBrush (Pixologic) Engine 4 Software (Epic	Intervention

								Games)	
Han, S-H. [20]	2019	Single (during chest radiography, after VR or verbal instruction intervention).	Chest radiography (x-ray)	**Control Group**: Received **simple verbal instruction** before chest radiography. **VR Group**: Received a **3-minute immersive VR education** explaining the radiography process.	VR education significantly reduced anxiety and distress in pediatric patients undergoing chest radiography. Lower distress scores in the VR group (OSBD score: 2.0 vs 5.0 in control, p = 0.004). Lower need for parental presence (16.3% in VR groups vs. 36.0% in control) Shorter procedure time (55.1s in	Anxiety and distress: Observational Scale of Behavioral Distress (OSBD) (0-30 scale) Need for parental presence (yes/no) Parental satisfaction score (0-10 scale) Procedure time (seconds from room entry to image capture). Number of repeated radiographs Process difficulty score	Oculus Go VR headset	Custom VR content developed by JSC Games (Seoul, Republic of Korea) Randomization software: Random Allocation Software (version 1.0, Isfahan University of Medical Sciences). Statistical analysis software: SPSS (version 21.0, SPSS Inc).	Pre-intervention: VR was used before chest radiography to educate and prepare pediatric patients

					VR group vs. 75.0s in control) Higher parental satisfaction (9.4 in VR group vs. 8.6 in control) Fewer repeated procedures in the VR group (8.2% vs 16.0%)				
Nambi G [32]	2020	Dual (Baseline and after 4 weeks)	3-T MRI Ultrasound Device (Hitachi Ultrasound, Tokyo, Japan)	Immunosorbent assay (ELISA)	Positive effects of VR training on imaging and biochemical aspects of study subjects.	Imaging (muscle cross-sectional area, muscle thickness) Biochemical (CRP, TNF,-alpha, IL-2, IL-4, IL-6)	Imaging (muscle cross-sectional area, muscle thickness) Biochemical (CRP, TNF,-alpha, IL-2, IL-4, IL-6)	VR: ProKin system (PK 252, N Tecno Body, Italy)	Intervention
Milano, E.G.[29]	2021	Single	CMR, cardiac magnetic resonanc	n/a	3D pdf this reached only 70%, whereas it	LVOT max, RVOT max	models were printed at 1:1 scale, in rigid white nylon (EOS PA2200	The 3D reconstructions (as .obj files) were imported	Pre-surgical

			e; CT, computed tomography		was 95% after VR. Virtual reality can enhance understanding of suitability for biventricular repair in patients with complex DORV if compared to cross-sectional images and other 3D modelling techniques.		Nylon 12) using selective laser technology (EOS P100).	into a novel VR environment developed in-house within the Unity engine. The target platform was the Oculus Rift system (comprised of a headset, two sensors, and two hand controllers).	
Stunden, C. [26]	2021	Dual	Ultrasound	**virtual reality (VR)-based simulation training vs**	virtual reality (VR)-based simulation training was as effective as standard training methods for ultrasound-	MoTrak head motion tracking system, Venham picture test, short State-Trait Anxiety Inventory, procedural data (minutes),	MERGE VR Headset, Samsung Galaxy S9	Unity, AirServer Connect	Pre-surgical

				standard training method	guided regional anesthesia. The study found no significant difference in the clinical performance between the two groups, suggesting that VR-based training can be a viable alternative to traditional training methods for developing skills in this area.	usability, child reported satisfaction and fun			
Ryu, J-H [21]	2021	Single (during chest radiography, after	Chest Radiography (X-ray)	Tablet group: watched a 3-minute	VR education significantly reduced distress and anxiety in pediatric	Anxiety and distress: Observational Scale of Behavioral Distress (OSBD)	VR group: Head-mounted VR display Tablet group: Tablet PC for video	Custom VR content developed based on a simulated radiology	Pre-intervention: VR was used before chest radiography

		the VR or tablet video intervention)		educational video on a tablet explaining chest radiography VR group: received the same educational content in an immersive VR environment using a head-mounted	patients compared to tablet video education Lower distress scores in the VR group (OSBD score: 1.0 vs. 4.0 in the tablet group, p < 0.001) Lower OSBD distress scores in the VR group (median 1.0) vs. the tablet group (median 4.0) (p < 0.001) Lower need for parental presence (8.3% in the VR group vs. 31.7% in the tablet group,	(0-30 scale) Need for parental presence (yes/no) Parental satisfaction score (0-10 scale) Number of repeated radiographs Process difficulty score Ease-of-procedure score (0-10 scale rated by radiology technologists)	education	room experience Tablet video was 2D conversion of the same VR material Randomization software: Random allocation software (version 1.0, Isafahan University of Medical Sciences) Statistical analysis software: SPSS (version 21.0, SPSS Inc.)	to educate and prepare pediatric patients

				display	p = 0.001) Shorter procedure time (48s in the VR group vs. 65s in the tablet group. p < 0.001) Easier procedure for radiology technologists in the VR group (ease-of-procedure rating 10.0 vs. 8.0, p < 0.001) Fewer repeated chest radiographs in the VR group (3.3%) vs. the tablet group (10%) (				
Sadri, S [27]	2023	Dual	CT and fluoroscopy	AR guidance vs	AR guidance significantly reduced	Primary outcomes measured	Microsoft HoloLens	Unity, 3mensio	Intervention

				standard guidance	contrast volume used during device deployment without increasing the time required for filter placement or fluoroscopy time. The AR system facilitated easier device placement and increased confidence in navigating the aortic arch during the procedure.	include iodinated contrast volume, times to filter placement, and fluoroscopy time. Secondary outcomes involve creatinine levels at discharge and clinical adverse events such as stroke and death at 30-day follow-up.			
Chuan, A [19]	2023	Single (within this session, each	Ultrasound	Novice group (participants with no	Experienced participants performed slightly better than	Needling performance scores, calculated based on needle	VR Headset: Oculus Rift S Hand controllers (to manipulate	Unity C# (for VR trainer development)	Pre-surgical (VR trainer was designed for training in

		participant performed 40 needling attempts across four different virtual nerve targets		prior experience in ultrasound-guided regional anesthesia (UGRA) vs. experienced group: participants with at least 50 ultrasound guided regional anesthesia proced	novices (p = 0.002) Performance scores remained above 80% for experienced participants from the third attempt onward, while novices showed more variability. **VR trainer immersion** was comparable to other **high-fidelity VR software i**n realism, quality of interface, and possibility to act **(**p > 0.06). The VR trainer	angulation (ideal in-plane positioning), number of withdrawls (fewer is better), time taken to complete the task Presence Questionnaire (for immersion in the virtual environment) NASA Task Load Index (NASA-TLX) (for cognitive workload)	virtual transducer and needle) Motion Capture System: MTw Awinda (Xsens, Netherlands) Ultrasound Machine: Edge (FujiFilm SonoSite, Bothell, WA, USA) Computer: Gaming laptop with Intel Core i7-8750H processor (2.2 GHz) 16GB RAM NVIDIA GeForce GTX 1060 graphics card	SPSS version 24 (for statistical analysis) MedCalc version 20.115 Microsoft Excel (2009 version) NASA-TLX software (iOOS version 1.03) for cognitive workload measurement	ultrasound guided regional anesthesia (UGRA), not for direct intervention on patients

				ures performed	imposed workloads similar to real-life procedural medicine (p = 0.53) Novices exhibited greater initial learning improvements compared to experienced participants, who had more stable performance.					

Table 2: Standard for Reporting of Diagnostic Accuracy (STARD) consensus scores for primary studies of this review.

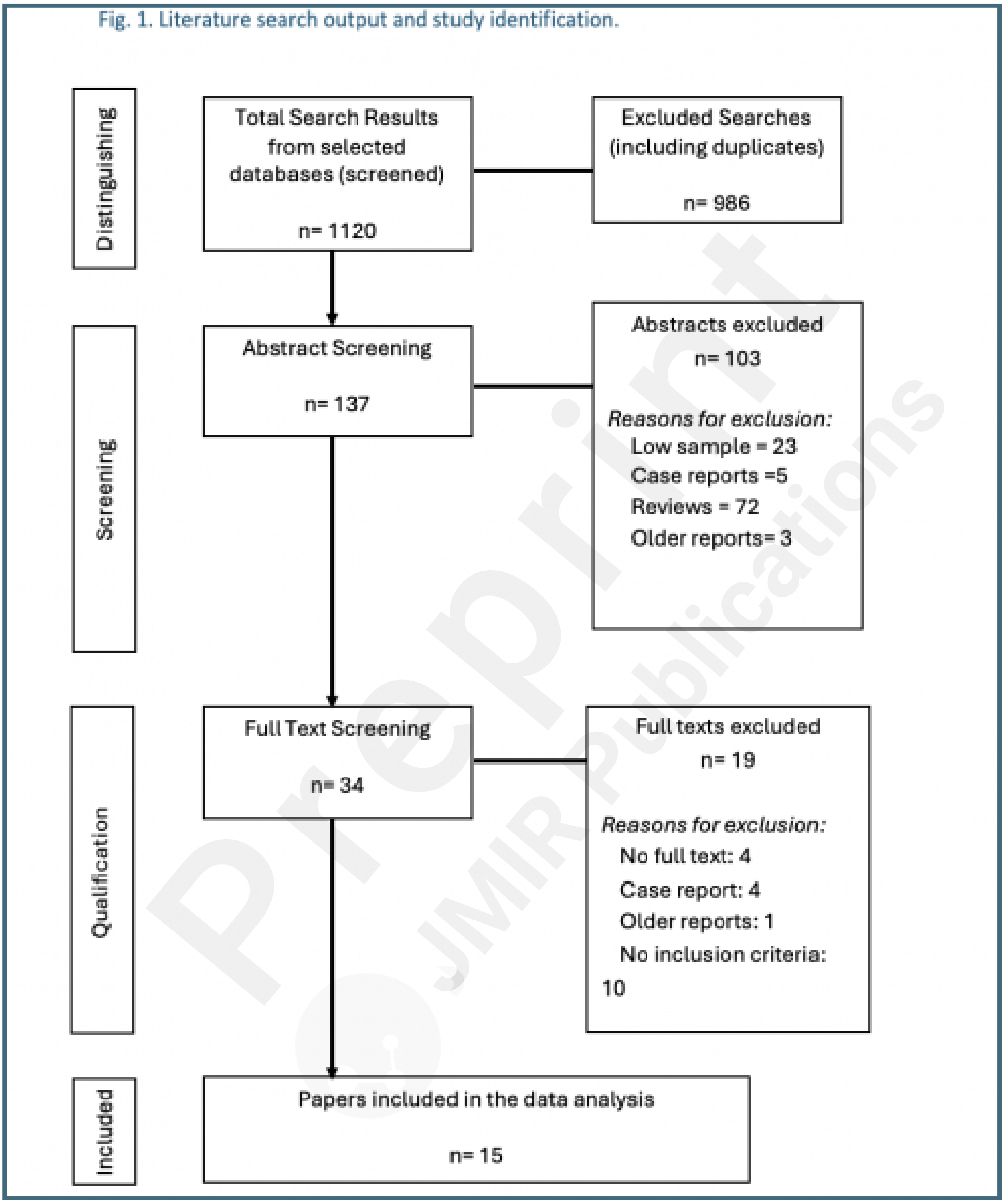
First Author	Year of Publication	STARD Score
Kockro R [23]	2000	61%
Hohlweg-Majert B [24]	2005	42%
Qui TM [30]	2010	79%
Ieiri S [28]	2012	53%
Souzaki R [25]	2013	50%
Zhao C [31]	2015	66%
Simpfendorfer T [18]	2016	53%
Yang JH [22]	2019	89%
Han S-H [20]	2019	84%
Nambi G [32]	2020	87%
Milano E [29]	2021	63%
Stunden C [26]	2021	84%
Ryu J-H [21]	2021	79%

Sadri S [27]	2023	71%
Chuan A [19]	2023	74%

Supplementary Files

Figures

Literature search output and study identification.



Multimedia Appendixes

Tables: Table 1–A: Baseline demographic data, study year, study design, and key findings of the selected primary papers of this review. Table 1–B: Information about number of timepoints, imaging modality, comparators, key findings, measurements, and hardware and software used in the virtual reality instrumentation of the selected primary studies of this review. Table 2: Standard for Reporting of Diagnostic Accuracy (STARD) consensus scores for primary studies of this review.
URL: http://asset.jmir.pub/assets/27d27f327d949987c5156695bd2e3fe1.docx