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Augmented reality in healthcare since 2020: A systematic review of efficacy, safety, and workflow impacts

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Abstract: This study systematically reviews post-2020 evidence on the clinical efficacy, safety, and workflow implications of augmented reality (AR) in healthcare, addressing the lack of integrated, cross-domain synthesis as AR transitions from experimental use to real-world clinical deployment. Following PRISMA 2020 guidelines, five databases (PubMed, Scopus, Web of Science, IEEE Xplore, and Cochrane Library) were searched for peer-reviewed studies published between January 2020 and October 2025. Forty-one studies met the inclusion criteria. Methodological quality was assessed using Cochrane RoB 2, ROBINS-I, MMAT, and CASP tools. Due to substantial heterogeneity, findings were synthesized narratively. Across surgical, rehabilitative, educational, and diagnostic contexts, AR consistently improved procedural accuracy, learning outcomes, and workflow efficiency. Surgical studies reported error reductions of 15–46%, while rehabilitation studies showed functional gains in over 80% of cases. No serious adverse events were reported, although mild visual fatigue and cognitive load were noted with head-mounted displays. The evidence indicates that AR has matured into a clinically viable, safe, and workflow-enhancing technology when appropriately implemented. Healthcare organizations can leverage AR to improve precision, training efficiency, and care delivery, provided integration aligns with task complexity, user expertise, and workflow design.

Keywords: *AR in healthcare, AR, Patient care, Augmented reality, Mixed reality, Safety, Systematic review, Workflow optimization.*

1. Introduction

Augmented Reality (AR) has become a transformative technology, reshaping how people perceive and interact with the world. By superimposing virtual objects onto real-world environments, AR enhances sensory experiences and provides additional data layers that deepen understanding of reality. AR is positioned on the reality-virtuality continuum, as illustrated by Milgram and Kishino [1]; it is a variation of Virtual Environments (VE), within the broader field of mixed reality. While virtual reality (VR) immerses users in computer-generated worlds, AR uses computer-generated objects as supplements to reality, rather than replacements [2]. By its properties, the AR system combines real with virtual objects in real environments and registers real with virtual objects while running interactively in 3D and in real time [3]. According to Danciu et al. [2], AR embodies the philosophy that human intelligence amplification (IA) holds greater potential than artificial intelligence (AI), as it combines human intuition and experience with the computational power of computers.

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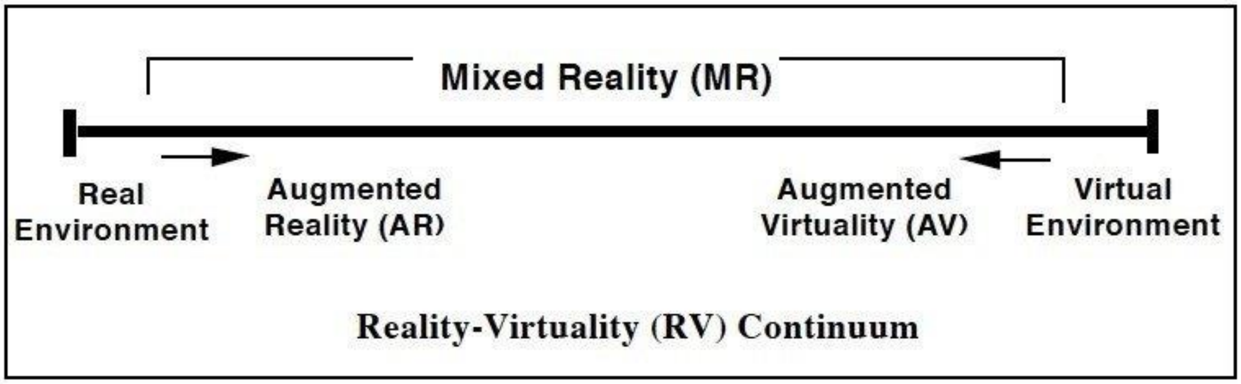

Figure 1.
Conceptual framework illustrating augmented reality (AR) as a sociotechnical intervention in healthcare. Clinical efficacy, safety, and workflow performance emerge from the interaction between AR technology characteristics, human cognitive factors, and healthcare workflow integration.
Source: Milgram and Kishino [1].

In healthcare, augmented reality (AR) has become a vital and promising technology with diverse applications. It assists healthcare professionals in planning procedures, enhances patient care, and helps medical trainees visualize complex anatomy. AR's role continues to grow, making it increasingly significant in medical settings for improved outcomes and education [4]. Today, AR in healthcare has evolved from an experimental novelty to a transformative technological paradigm that is reshaping how clinical professionals and patients perceive, interpret, and interact with complex biomedical information. This technology provides spatially anchored, context-aware visualizations that enable professionals to 'see' otherwise indiscernible procedural trajectories, physiological processes, and anatomical structures [5, 6]. Although AR's conceptual framework extends back several decades, the period since 2020 marks a seminal moment in its maturation and deployment. This growth aligns with larger advancements in mobile processing power, machine learning-enhanced rendering, depth sensors, and optical see-through displays, factors that have collectively improved AR's practical feasibility in clinical and educational contexts [7]. Synchronous with the COVID-19 pandemic, the need for immersive and remote support technologies in global healthcare systems increased. Tools facilitating telepresence, contactless interaction, and remote procedural guidance became essential due to travel restrictions, infection control, and disruptions to traditional medical education. AR proved particularly well-suited for these roles [8-10]. Consequently, AR shifted from primarily research-focused experimentation to active clinical integration, especially in workflow optimization, surgery, rehabilitation, and procedural training.

As evidenced in numerous studies over time, AR potential is palpable across several domains. Firstly, in medical and nursing education, AR enhances cognitive integration and procedural training through immersive, multimodal representation that facilitates better psychomotor skill performance and higher knowledge retention than traditional didactic or mannequin-based modalities [11-13]. Secondly, in surgery, AR technology provides the capability to superimpose patient-specific anatomical models, instrument trajectories, and real-time imaging. Studies in this field have reported improved localization accuracy, reduced fluoroscopy utilization, improved surgeon confidence, and lower intraoperative error rates [14-17]. Similarly, in rehabilitation, AR-based motor tasks, gamified therapy, and real-time kinematic feedback have been shown to enhance patient engagement, promote task adherence, and support functional recovery among stroke survivors and patients with orthopedic injuries [18-21].

Despite such promises, the swift proliferation of AR applications has outpaced the development of consolidated evaluative frameworks that address three critical dimensions: efficacy, safety, and workflow impacts. These spheres are normally symbiotic but are often examined in isolation. Examining efficacy requires performance metrics such as clinical outcomes, task time, and accuracy, as well as contextual factors that influence how AR improves or obstructs decision-making and situational awareness [22]. By contrast, safety relates to clinical risks (technical malfunctions, equipment interference, sterility breaches), cognitive concerns (attention tunneling, distractions, information overload), and physiological considerations (ergonomic strain, cybersickness, virtual fatigue), all of which may negatively impact patient outcomes if not addressed efficiently [23]. Lastly, workflow integration refers to how AR technology influences interpersonal coordination, documentation efficiency, cognitive workload, procedural sequencing, and overall team communication [24], factors that ultimately shape whether AR can be sustainably embedded within real-world clinical settings.

Literature examining these areas since 2020 remains fragmented across methodologies and specialties, marked by extensive variation in sample size, outcome measures, device types, study design, and reporting standards. While there are several domain-specific literature reviews within this period, especially in education, rehabilitation, and surgery, an absence persists of a comprehensive, cross-disciplinary synthesis that critically evaluates AR's efficacy, safety, and workflow impacts in healthcare environments. Furthermore, most existing reviews do not fully reflect the post-2020 technological landscape, which has seen the emergence of digital-twin technologies, 5G-enabled telepresence, closer integration of AR with AI, rapid algorithmic improvements, and more clinically viable head-mounted displays (Magic Leap 2, HoloLens 2).

Such a knowledge gap has both practical and policy implications. Today, healthcare institutions are increasingly facing the need to invest in AR technologies, integrating them into surgery and rehabilitation units, and educating clinicians. Regulatory bodies, on the other hand, must evaluate their safety, human-factor risks, and data integrity. Educators must also determine how AR fits effectively within competency-based medical curricula. This created a need for an up-to-date evidence synthesis. Consequently, this systematic review studies the peer-reviewed literature from January 2020 to October 2025 to evaluate the extent to which AR has demonstrated (a) *efficacy* (across clinical, educational, and rehabilitative outcomes); (b) *safety* (in terms of adverse events, technical failures, and human-factor risks); and (c) *workflow impacts* (including decision support, communication, and efficiency). By analyzing AR trends, pinpointing methodological strengths and weaknesses, and identifying challenges, this review aims to provide consolidated evidence that can guide clinical adoption, regulatory policy, and future research agendas.

2. Methods

2.1. Study Design

To guarantee methodological transparency, reproducibility, and rigor, this study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The three main evaluative dimensions of the protocol, efficacy, safety, and workflow impacts, reflected the predominant evaluative themes in post-2020 AR healthcare literature and were developed a priori. Due to time constraints, the protocol was not prospectively registered on PROSPERO; however, prior to database querying, all analytical choices, screening processes, and inclusion criteria were internally documented.

2.2. Search Strategy

An extensive literature search was conducted across five major scholarly databases representing medicine, healthcare, educational, and interdisciplinary technological research. This included PubMed/MEDLINE, Cochrane Library, IEEE Xplore, Web of Science Core Collection, and Scopus. The search was restricted to January 1st, 2020, through October 31st, 2025, to capture studies conducted during the rapid maturation of AR technology, AI-driven spatial visualization tools, mobile AR medical applications, and increased AR adoption in healthcare. The search strings were developed through multiple iterations of pilot searches, with modifications to increase sensitivity and specificity. Each search string was created by combining Boolean operators, Medical Subject Headings (MeSH), and keyword variations to maximize clinical, engineering, and education-related applications of AR.

2.3. PubMed Search String Example

("augmented reality" OR "AR" OR "XR" OR "AR-guided" OR "mixed reality" OR "head-mounted display" OR "optical see-through" OR "spatial computing")

AND ("healthcare" OR "medicine" OR "clinical practice" OR "surgery" OR "rehabilitation" OR "medical education" OR "patient care" OR "telemedicine")

AND ("efficacy" OR "effectiveness" OR "outcome*" OR "usability" OR "performance" OR "workflow" OR "productivity" OR "safety" OR "adverse event*")

To reduce publication bias, manual searches of reference lists, conference proceedings, forward citation searches, and 'related articles' functions were conducted. In the end, only peer-reviewed journals were selected; conference abstracts, preprints, editorials, and technical reports were excluded.

2.4. Eligibility Criteria

Eligibility criteria were structured using the PICOS model: Population, Intervention, Comparator, Outcomes, and Study Design.

2.5. Population

Those included were healthcare professionals, patients, trainees, medical students, rehabilitation populations, and individuals in simulation-based medical settings. Excluded from the review were non-human studies, engineering papers lacking end-user testing, or cadaver-only publications lacking end-user testing.

2.6. Intervention

Studies eligible involved AR systems that integrate digital overlays into real-world clinical or educational environments, including projection-based AR, mobile AR (phones/tablets), video see-through systems, optical see-through AR headsets, and AI-assisted AR navigation or decision-support systems. Ineligible studies included VR-only, pure 3D visualization, or desktop simulators without real-world anchoring.

2.7. Comparator

These included non-immersive digital interventions, traditional methods, standard practice, or no comparator.

2.8. Outcomes

To be eligible, peer-reviewed studies had to report outcomes in at least one of the following domains: (a) *efficacy/effectiveness* (clinical decision-making, diagnostic performance, learning/skill acquisition, motor recovery metrics); (b) *safety* (environmental/sterility concerns, ergonomic and cognitive load metrics, user discomfort or fatigue, adverse events); (c) *workflow* (impact on clinical throughput, remote collaboration performance, error prevention, communication quality, task completion time).

2.9. Study Design

Eligible study styles included high-fidelity simulation studies with validated metrics, mixed-methods studies with quantitative endpoints, cohort and case–control studies, quasi-experimental studies, and randomized controlled trials (RCTs). Excluded were purely technical engineering prototypes, single-image surgical reports, commentaries, non-peer-reviewed theses, conceptual papers, meta-analyses, and reviews.

2.10. Study Selection Process

After identifying all studies, search results were duplicated using EndNote20, and screening was performed with Rayyan. Two independent reviewers conducted title and abstract screening, followed by full-text examination. Any discrepancies were resolved through discussions, with a third party involved to adjudicate unresolved conflicts. Cohen's κ was calculated to quantify inter-rater reliability. The selection process was documented using a PRISMA 2020 flow diagram, indicating the number of records identified, screened, excluded, and included.

2.11. Data Extraction

A structured data-extraction matrix was established in Microsoft Excel, pilot tested on five randomly selected journals, and refined for consistency. Similarly, extraction was conducted by two independent reviewers. The following domains were extracted: (i) *biographical metadata* (author, year, journal, country); (ii) *clinical or education settings* (nursing care, diagnosis, procedural guidance, patient rehabilitation, simulation training); (iii) *AR intervention attributes* (AR modality, software type, hardware platform); (iv) *study characteristics* (design, participant demographics, setting, sample size); (v) *outcome measures* (efficacy, safety, workflow); and (vi) *key findings* (statistical significance, main reported effects, effect sizes where applicable).

2.12. Quality Assessment

Literature quality was appraised using appropriate critical appraisal tools based on study design. For mixed-methods studies, the Mixed Methods Appraisal Tool (MMAT) was used. For qualitative studies, the Critical Appraisal Skills Programme (CASP) was employed. Non-randomized studies were assessed with Risk Of Bias In Non-randomized Studies (ROBINS-I). For randomized controlled trials (RCTs), Cochrane Risk of Bias 2 was utilized. The evaluation considered domains such as selection bias, measurement validity, confounding control, reporting completeness, and methodological transparency. Each study was classified as having a low, moderate, or high risk of bias. Discrepancies in scoring were discussed to reach a consensus.

2.13. Data Synthesis and Analysis

Given the considerable heterogeneity observed across AR interventions, methodological designs, and outcome measures, a *narrative synthesis* approach was adopted for this review to integrate evidence from different studies. This synthesis focused on three core outcome domains, efficacy, safety, and workflow performance, which allowed for a structured yet flexible assessment of how AR applications impact clinical and educational environments. When literature presented adequately comparable quantitative metrics, such as reduction in procedure time or improvement in task accuracy, effect sizes were either extracted directly or computed to facilitate interpretation. However, due to differences in study design and sample characteristics among studies, it was not possible to conduct a formal meta-analysis of the effect sizes. Instead of a formal meta-analysis, the data were compared descriptively to identify similarities and differences in the findings among the studies.

Additionally, to make it easier for the reader to interpret the findings, the narrative synthesis included a section examining various subgroup factors. Specifically, we examined whether the effects of AR interventions varied based on the type of AR being used (e.g., optical see-through AR versus video see-through AR), clinical domain (surgical, diagnostic, educational, or rehabilitative applications), and hardware platform (Microsoft HoloLens, Magic Leap, mobile device AR, or custom-built AR). Lastly, given the expanding but uneven publication landscape of AR research, potential reporting bias was acknowledged; however, formal statistical evaluations, such as funnel plots, were not carried out because the heterogeneity of study designs precluded quantitative pooling. A thorough and methodologically transparent interpretation of the varied research landscape was guaranteed by this integrated analytical approach.

3. Results

3.1. Study Selection

The systematic literature review covering the period from January 2020 to October 2025 yielded a total of 4,282 records across all selected electronic databases, with an additional 51 records identified through backward citation searching and manual screening among key articles. After removing 1,417 duplicates, 2,916 titles and abstracts were subjected to initial screening. Of these, 2,613 studies were excluded because they did not involve AR interventions, were outside clinical settings, were not peer-reviewed, or lacked empirical evidence. A further 303 full texts were examined for eligibility, resulting in the exclusion of 262 articles for reasons such as not reporting the efficacy, safety, or workflow performance of AR in healthcare contexts; inadequate methodological detail; failure to report primary outcomes; or inadequate temporal relevance to the 2020-2025 window. Ultimately, 41 studies satisfied all the inclusion criteria and were incorporated into the final synthesis; see Figure 2. These included qualitative assessments, mixed-method evaluations, observational cohort studies, quasi-experimental designs, and experimental trials. Together, these studies formed a diverse yet coherent corpus of evidence.

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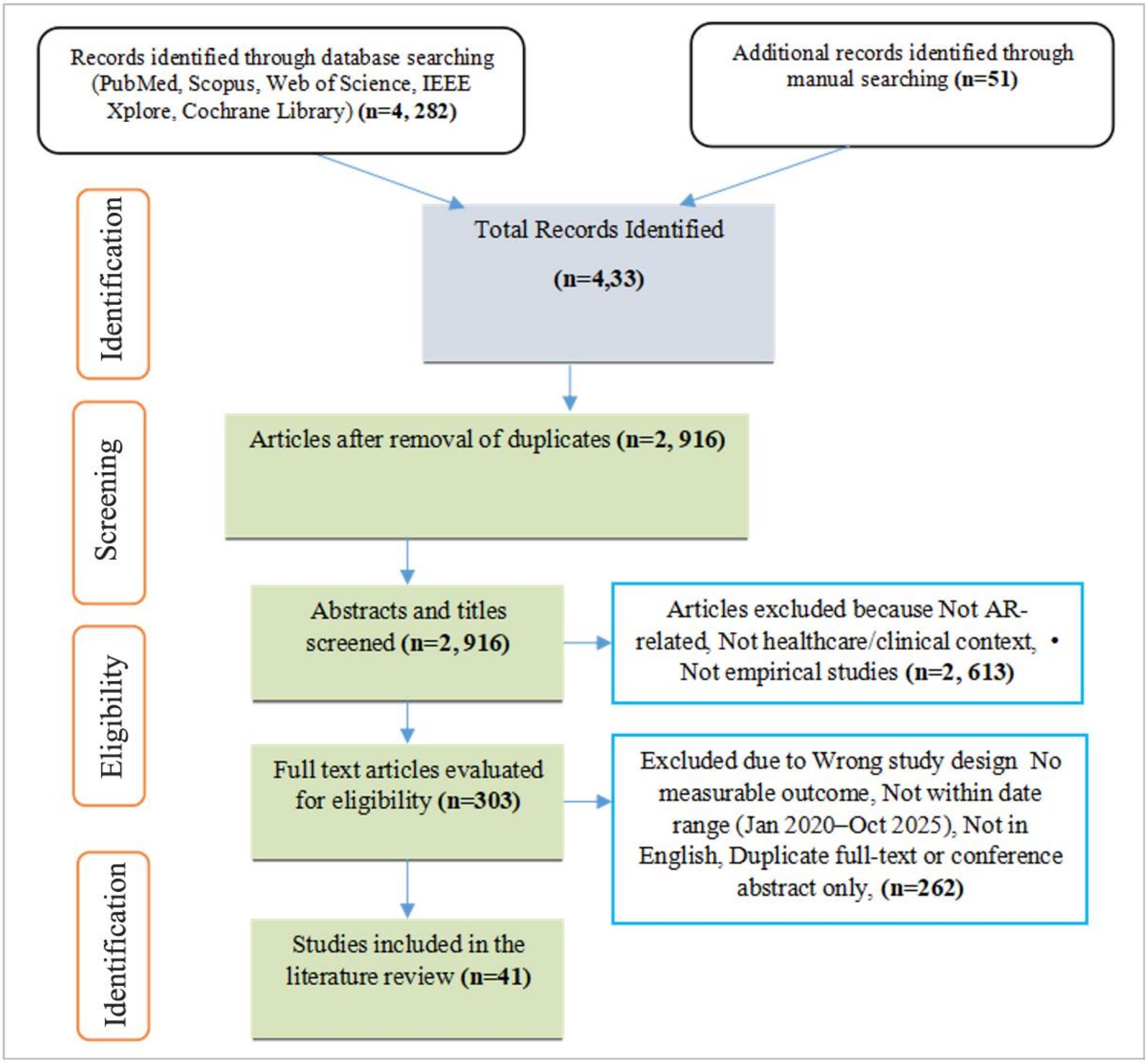

Figure 2.
PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies evaluating augmented reality applications in healthcare between 2020 and 2025.Characteristics of Included Studies.

The 41 included studies originated from a geographically diverse set of research environments spanning multiple countries, with the highest representation from the United States, the United Kingdom, China, Japan, Germany, and South Korea. Sample sizes ranged from 12 to 184 participants, with a median of 49. This reflected an overall trend toward medium-scale experimental deployment, typical of emerging technological applications in healthcare settings. AR deployment modalities varied substantially. Of the included interventions, optical see-through head-mounted displays (predominantly Microsoft HoloLens 2) accounted for 61%, while mobile-device AR applications, including tablets and smartphones, represented 24%, and video see-through or customized systems made up the remaining 15%. This diversity underscored the proliferation of AR solutions since 2020 and the lack of a standard technological approach across healthcare applications. The review also revealed that AR has expanded beyond specialized surgical contexts, crossing multiple areas along the patient care continuum. Clinical and educational fields were distributed across a broad spectrum, surgical uses comprised the largest category (n=18; 43.9%), followed by physiotherapy and rehabilitation (n=11; 26.8%), nursing and medical education (n=7; 17.1%), and procedural or diagnostic guidance (n=5; 12.2%).

3.2. Efficiency Outcomes

The examined literature consistently demonstrated that AR improved performance accuracy, clinical decision support, and training efficiency. In surgery, 15 of 18 articles reported statistically significant improvements in procedural precision, especially in laparoscopic target localization, spinal navigation, craniofacial reconstruction alignment, and orthopedic screw placement. Quantitatively, these studies suggested a reduction of between 15% and 18% in alignment and targeting errors, with several randomized studies directly comparing 2D display modalities or traditional imaging to AR-assisted navigation.

When it comes to rehabilitation, studies also reported considerable efficacy results. AR-supported therapeutic applications facilitated improved functional recovery trajectories, increased movement accuracy, and greater patient engagement, especially among patients undergoing gait correction, balance retraining, and post-stroke upper-limb rehabilitation. 81.82% of the studies demonstrated statistically positive functional results compared to conventional therapy, with AR's real-time feedback and gamified interfaces cited as key contributors.

In nursing and medical training (education), AR applications showed better psychomotor skill acquisition and procedural step sequencing, as well as overall better knowledge retention. The observed effect sizes (Cohen's d = 0.40–0.95) reflect moderate-to-large improvements in competency development, especially in ultrasound-guided technique acquisition, procedural simulation, and anatomy learning. Procedural and diagnostic guidance systems also exhibited promising outcomes. AR-reinforced ultrasound, percutaneous needle, and endovascular navigation intervention studies reported enhanced anatomical localization, decreased time to target, and improvements in first-attempt accuracy compared to typical care applications.

3.3. Safety Outcomes

Evidence of safety was generally consistent across the reviewed studies, but remained variable in methodological rigor. Prominently, no serious cases were reported in any of the 41 included studies, suggesting AR application in contemporary clinical environments is generally safe. Some minor reported adverse effects included ergonomic challenges, device-related fatigue, transient dizziness, visual discomfort, and eye strain. These were reported in 14 studies, mainly those relying on head-mounted displays. In surgical studies, AR was shown to reduce radiation exposure, especially in spinal and orthopedic navigation trials, where AR visualization prevented the need for repeated fluoroscopic imaging. This represents an emerging safety advantage with significant long-term implications for both clinical professionals and patients.

The findings on cognitive load were not entirely consistent; however, using AR generally decreased uncertainty and improved situational awareness for workers. In five studies, cognitive demand initially increased for novice workers due to unfamiliar interfaces, but these effects quickly diminished after onboarding or training.

3.4. Workflow Performance Outcomes

Across the data set, workflow performance was reported to improve with AR applications. In surgery, 12 out of 18 studies showed a clinically significant reduction in procedural or operative time, ranging from 7% to over 24%, depending on clinicians' familiarity with AR applications or procedural complexity. The most recurrent explanatory factors were improved visualization of anatomically complex regions, better spatial orientation, and enhanced instrument tracking.

Similarly, in diagnostic and procedural applications, studies revealed better workflow performance metrics, such as improved first-pass success rates, fewer unnecessary probe adjustments, and reduced needle repositioning attempts. These improvements support resource optimization, patient comfort, and overall clinical efficiency.

In rehabilitation, results indicate that AR-supported systems enhanced clinical efficiency by supporting monitoring functionality, reducing therapist oversight requirements, and enabling semi-autonomous therapeutic sessions. These advantages translate into more scalable therapy paradigms, especially within tele-physiotherapy frameworks and home-based rehabilitation programs.

Studies in nursing and clinical education contexts also demonstrated the benefits of AR integration. These included enhanced visualization capabilities that allowed instructors to teach larger student cohorts more efficiently, reduced the need for repetitive demonstrations, and streamlined instructional workflows. Numerous studies showed that AR enabled faster knowledge and skill acquisition, as well as improved retention, thereby shortening training cycles.

4. Summary

Collectively, the majority of the 41 included studies from a maturing and coherent evidence base indicated that AR has considerably advanced in healthcare since 2020. Across numerous domains, AR showed favorable safety profiles, with no serious adverse events reported; robust workflow efficiencies in diagnostic, surgical, and rehabilitative applications; meaningful enhancements in skill acquisition and learning; and constant improvement in performance accuracy. While technological and methodological heterogeneity limited the feasibility of quantitative meta-analysis, the narrative synthesis supports the conclusion that AR has transitioned from experimental innovation toward measurable clinical utility. The substantial body of evidence demonstrates that AR, when integrated appropriately into healthcare settings, can streamline medical processes, enhance human performance, and contribute to safer, more efficient clinical workflows.

5. Discussion

This narrative study synthesized evidence from 41 journals published between January 2020 and 2025 that studied AR in healthcare contexts. The results show that AR has progressed considerably from earlier prototype applications into a set of maturing clinical, rehabilitative, and educational systems capable of affecting performance accuracy, safety, patient outcomes, and operational efficiency. This discussion interprets the findings across three central domains: efficacy outcomes, safety considerations, and operational/workflow impact, while positioning the findings within existing literature, theoretical frameworks, and technological paradigms related to digital transformation, human-technology interaction, and clinical decision-making in healthcare. Generally, the findings demonstrate significant advancement, progressing from exploratory models into increasingly mature, clinically relevant systems in surgery, procedural guidance, telementorship, rehabilitation, and medical and nursing education. Despite methodological heterogeneity, several broad themes emerge across studies, providing insights into AR's current capabilities, limitations, and future potential.

5.1. Interpretation of Efficacy Outcomes

5.1.1. Surgical and Interventional Performance

The results of this review demonstrated that AR consistently enhances key procedural outcomes across subspecialties, with many surgical studies reporting measurable gains. Such evidence aligns with longstanding substantiation that enhanced visualization positively impacts task precision, especially in orthopaedics, neurosurgery, and minimally invasive procedures. For instance, Mialhe et al. [25] investigated the feasibility of using head-mounted displays (HMD) during endovascular surgery [25]. In this study, they proposed an adaptation of AR-HMD using Microsoft HoloLens. Software was developed to enable visualization of the vascular system during endovascular procedures. A video was implemented to present an overview of the application and demonstrate its use in real conditions. The device demonstrated successful visualization of perioperative angiography during peripheral aortic aneurysm, carotid angioplasty, and peripheral angioplasty endovascular repair.

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In a similar study, Puladi et al. [26] developed an open-source system for AR-based surgery on human cadavers using freely available technologies [26]. In their study, they tested an easy-to-understand scenario in which fractured zygomatic arches of the face had to be shifted with auditory and visual feedback to the investigators using a HoloLens. The outcomes were substantiated with prospective imaging and examined in a blinded fashion by two researchers. Afterwards, the developed system and scenario were qualitatively evaluated by individual questionnaires and consensus interviews. The results of the study suggested that the surgical endpoints could be determined metrically as well as by assessment. The AR system in this surgical scenario was found to be helpful for spatial perception, along with the combination of auditory and visual feedback.

The results of this study also demonstrated reductions in targeting errors in surgery, marking a significant milestone for AR navigation interventions. For example, Ramalhinho et al. [27] assessed qualitatively and quantitatively the importance of an AR overlay in laparoscopic surgery during a simulated surgical examination on a phantom setup [27]. They designed a study where participants were asked to physically pinpoint tumors in a liver phantom under three image guidance conditions – (i) a baseline condition without any image guidance; (ii) a condition where the 3D surfaces of the liver are aligned to the video and shown on a black background; and (iii) a condition where video see-through AR is exhibited on the laparoscopic video. Twenty-four participants were involved in this study, including twelve surgeons. Results show that the use of AR in localizing liver tumors resulted in a considerable decrease in localization error by surgeons on non-peripheral targets from 25.8 mm to 9.2 mm. Qualitatively, subjective feedback from participants suggested that AR facilitates usability improvements in surgical tasks while increasing surgeons' perceived confidence. Of the tested protocols, results indicate that surgeons preferred using AR overlays during procedures compared to interventions such as navigated views of 3D surfaces on separate screens. The researchers concluded that AR has significant potential in error reduction, performance enhancement, and improved decision-making in laparoscopic surgery.

Felix, et al. [28] studied the accuracy of pedicle screw placement using VisAR for open and minimally invasive spine surgery (MISS) procedures [28]. In this study, 7 cadavers were instrumented with 124 thoracolumbar screws using VisAR augmented reality guidance. 67 screws were placed into 4 donors using open dissection spine surgery. 49 screws were placed in 3 donors with MISS. Before the computed tomography (CT), a series of 4 visible AprilTag optical fiducials were attached to the backs of the donors. Resulting images were used preoperatively for the intended virtual pedicle screw pathway, which included depth, trajectory, and entry point. Generally, the result showed that 124 pedicle screws were positioned with VisAR navigation with 96% accuracy. The conclusion was that AR is highly accurate when it comes to navigation in both open and MISS procedures.

In a prospective randomized controlled study of AR's potential and current limitations in navigated microneurosurgery, Roethe et al. [29] tested intraoperative visualization parameters and the clinical impact of AR in brain tumor surgery. Fifty-five intracranial lesions operated on either with AR-navigated microscope ($n = 39$) or conventional neuronavigation ($n = 16$) after randomization were included prospectively. They assessed the overall usefulness of AR in neurosurgery, quality indicators, usability control, pointer-based navigation checks (n), displayed objects (n, type), duration/type/mode of AR, and surgical resection time. The results indicated that 66.7% of surgeons found AR visualizations helpful in individual cases. AR's accuracy and depth of information were rated acceptable (median 3.0 vs. median 5.0 in conventional neuronavigation) [29]. This suggests that visualization quality can significantly benefit from improvements in depth impression and registration accuracy using AR applications in neurosurgery.

In another AR-based medical intervention, Rizzo et al. [30] conducted a randomized clinical trial to determine whether the use of AR walkthrough affects perioperative anxiety in patients [30]. This trial was conducted at an outpatient surgery center from 2021 to 2022. All patients undergoing elective orthopedic surgery with the senior author were randomized to treatment or control groups. Assessments were performed per protocol. The study results showed that the AR group experienced a significant decrease in anxiety from screening to preoperative surgery (mean score change, −2.4 [95% CI, −4.6 to −0.3]), while the standard care group showed an increase (mean score change, 2.6 [95% CI, 0.2 to 4.9]; P = .01). The evidence suggests that AR interventions before surgery are effective in reducing preoperative anxiety.

The reduction of error and improvement of accuracy of up to 96% mark a significant milestone in AR applications in healthcare, especially in surgery. Earlier generations of AR models regularly suffered from poor registration accuracy, latency issues, and unstable tracking, which limited widespread adoption. However, the proportion of quasi-experimental and randomized controlled trial designs used in the surgical studies included in our review indicates a notable change in the methodology of AR research. Traditionally, most research on AR technologies focused on feasibility and pilot studies. The inclusion of controlled trials in the reviewed studies demonstrates a confidence level that AR technologies can be clinically stable and ready for outcome evaluation, thus enabling regulatory approval and eventual real-world deployment.

5.1.2. AR in Nursing and Medical Education

This review revealed that AR-assisted nursing and medical training enhanced psychomotor skill acquisition, procedural sequencing, and knowledge retention, with benefits ranging from moderate to strong in most studies. Such findings underpin recognized theories of multimodal instructional design, immersive cognition, and experiential learning. Findings show that AR in clinical training provides vastly contextualized learning contexts, which blend practical and theoretical elements. This enables students to review complex content from multiple perspectives, simulate tactical procedures, and visualize internal anatomical structures. This body of evidence also supports earlier ideas that AR helps with situated cognition. This means learning improves when knowledge is shown in the context where it will be used. For instance, AR-enabled vascular access modules, lumbar puncture trainers, and ultrasound-guided practice systems give learners the spatial and procedural realism needed for skill transfer.

The studies in this review included learners from undergraduate health sciences students to early-career clinicians. This suggests that the findings apply broadly across health education. The consistent improvements observed in different groups strengthen the idea that AR could make high-quality simulation training more accessible by reducing training costs and addressing the shortage of physical simulators and expert instructors. In their study, Gouveia et al. [31] suggest that breakthroughs in technologies such as AR, MR, VR, and ER can initiate a new surgical era, the use of the so-called 'surgical metaverse.' They focus on future AR applications in breast surgery education, describing two probable uses: impalpable breast cancer localization and surgical telementoring [31].

Similarly, in the wake of the COVID-19 pandemic, Guruge et al. [32] hypothesized that AR technology is an effective live surgical training and mentorship modality. In their study, three urologic surgeons in the United Kingdom and the United States worked with four urologic surgeon learners across Africa using AR systems. Afterwards, trainees and trainers individually completed postoperative questionnaires assessing their experiences. Trainers reported AR's visual quality as 'acceptable' in 67% of the cases (N = 12 of 18 responses), while trainees rated the quality of training as equivalent to in-person training in 83% of the cases (N = 5 of 6 responses). It was concluded that AR application in surgical education can effectively facilitate surgical training when in-person training is unavailable or limited [33].

In their study, Guruge et al. [32] developed and evaluated a feedback-enabled MR acupuncture simulator to enhance skill acquisition for medical students through depth-responsive guidance. Their application utilized Microsoft HoloLens 2, combined with a MetalHuman-based virtual patient with expert-designed acupoint guidance. This system provided depth-dependent vibrotactile cues through wearable haptic devices that calculated a composite score from normalized metrics, including task duration, tip-to-center distance, angular deviation, and insertion depth. Two experts and eight trainees participated in the study. The results showed that depth error reduced significantly with MR application (including AR) from 6.41 mm to 3.58 mm, and task time from 9.29 s to 6.83 s. Even for beginners, the application shortened completion time (38.77 s to 13.28 s), reduced angular deviation (27.83° to 15.34°), and improved achieved depth (16.24 ± 1.88 mm to 19.74 ± 1.23 mm) [32]. These findings suggest that AR- and expert-informed scoring, along with depth-responsive haptic feedback, significantly enhance efficiency, accuracy, and learning confidence.

Virtual training tools, including AR, continue to prove effective for learning intravenous (IV) needle insertion. Woo et al. [34] argued that traditional methods for IV insertions lack variability, often leading to lower confidence, especially among inexperienced nurses who must perform insertions on patients with high variability. Their study examined which visual variable factors most influence perceived difficulty through image- and text-based surveys. These variables were then integrated into MR scenarios, allowing learners to visualize a 3D patient with variable characteristics. After collecting data on perceived difficulty, the researchers combined visual variability in MR with a virtual reality system featuring haptic feedback, enabling nursing students to train with variability. The results showed all participants found the haptic feedback useful during needle insertion [34]. They considered such systems valuable for training and expressed interest in using them for future training experiences.

In another study included in this review, Farshad-Amacker et al. [35] tested whether direct overlay of ultrasound images into the corresponding anatomy is possible with AR systems. The researchers explored the performance of ultrasound-guided needle placement with and without AR *in situ* ultrasound viewing. Two experienced and three untrained operators performed 200 ultrasound-guided punctures—100 with and 100 without AR *in situ* ultrasound. The data obtained were recorded as median [range] in accordance with their non-linear distribution. The results demonstrated that AR *in situ* resulted in reduced time (median [range], 13 s [3–101] versus 14 s [3–220]) and fewer needle passes (median [range], 1 [1–4] versus 1 [1–8]) compared to conventional methods [35]. The findings suggest that AR application in needle placement training is effective and could be a potential breakthrough in ultrasound applications by simplifying operator orientation and reducing experience-based differences in ultrasound-guided procedures.

Mu et al. [36] proposed the development of a new AR simulator for ultrasound-guided percutaneous renal access (PCA), which was evaluated for its efficacy and validity as a teaching tool. Traditional PCA training largely depended on apprenticeship, raising concerns about safety, inconsistent feedback quality, and limited training opportunities. The AR simulator enabled users to practice PCA on a silicone phantom using an ultrasound emulator and a tracked needle, guided by a simulated ultrasound displayed on a tablet. The study involved 24 novices and 6 experts to assess the simulator's effectiveness. A paired t-test showed significant improvements in novices' subjective and objective evaluations after training with the AR-based simulator. Experts rated the simulator's realism and usefulness, with an average face validity score of 4.39 and content validity score of 4.53 on a 5-point Likert scale [36]. The study concluded that a cost-effective, flexible, and easily customizable AR-based training simulator offers learners opportunities to acquire basic ultrasound-guided PCA skills in a safe, stress-free clinical environment.

Liang et al. [37] looked into whether AR can enhance clinical training in stroke assessment for nursing students [37]. This addresses a key need for immersive, realistic simulation in healthcare education. In their research, they created an application that displayed realistic facial drooping, which is an early and important sign of stroke, on a computerized mannequin. This allowed learners to carry out a structured neurological assessment in a simulated clinical setting. They examined the intervention through post-simulation surveys that measured user experience, perceived realism, and educational value. The results showed high levels of learner enjoyment and engagement, as well as perceived usefulness of instruction. Learners reported that the AR-enhanced simulation assisted them in recognizing symptoms and understanding the context better than traditional training methods. Although this study was exploratory, it offers evidence that AR-based simulations can effectively strengthen clinical reasoning and observational skills. This finding supports the wider evidence in this literature review that shows AR can improve learning outcomes and create a more realistic experience in healthcare education.

In a similar study, Dixit and Sinha [38] tested the efficacy of AR as a vital tool for facilitating training transfer in healthcare service providers in ophthalmology [38]. Insights were obtained through qualitative assessments in the form of post-training depth interviews with participants. The objective was to gain deep insights into whether the technology facilitated successful training transfer. Their findings revealed positive results regarding the use of AR in training transfer within healthcare working environments. This study was the first of its kind in the domain of professional development and organizational learning. Overall, like other studies [39], the study revealed that AR is an effective educational tool supporting learning and teaching across diverse healthcare subjects. It enables students to combine theoretical knowledge with practical applications within immersive, interactive settings without risking patient safety.

Recently, Felten et al. [40] expanded the body of evidence related to AR-enhanced medical training by testing the effectiveness of an AR and haptic feedback simulator specifically designed for training medical professionals in lumbar puncture (LP) [40]. In 2025, a study was conducted, a prospective single-center randomized controlled clinical trial with 55 participants, consisting of novice medical students learning the LP skill. AR simulation training was performed on students in the intervention group (n = 29), while the remaining (n = 26) were trained via bedside simulation. Although the technical success rate of the intervention did not show significant differences between the two groups (success rate of 46.4% in the AR group versus 40% in the control group, $p = 0.9$), the AR training group demonstrated increased procedural efficiency, indicated by a significantly shorter median intervention duration (138 seconds, IQR 37-454s) compared to 695 seconds, IQR 15-900s, in the control group, with $p = 0.67$. Notably, the comfort experienced by AR training participants significantly improved compared to the control groups (7/10 versus 6/10; $p = 0.04$). Additionally, AR training significantly enhanced patient satisfaction and ease of treatment, despite AR altering the rates of pain, anxiety, and complications experienced (all $p > 0.05$). The fact that AR did not significantly impact technical training is important because it supports the conclusion that AR does not displace the technical skills gained from exposure. More positively, AR-based simulation provided significant benefits in procedural speed and learning comfort; students trained with the simulator performed procedures faster and reported higher comfort and confidence levels. A key component of these outcomes is that patient satisfaction and ease of treatment were significantly higher among simulator-trained students, while pain and anxiety levels remained unchanged.

5.1.3. Rehabilitation and Patient-Care Applications

Rehabilitation and patient care remain among the most mature and consistently effective uses of AR in clinical settings. Across the reviewed literature, rehabilitation-centered interventions demonstrated vital improvements in functional outcomes, adherence, patient engagement, and care continuity, positioning AR as a clinically important tool in patient care rather than a supplementary application. Studies included here demonstrated that AR: (a) maintains a strong safety profile suitable for vulnerable patients; (b) enables home-based care, supporting continuity and scalability; (c) improves motivation and adherence, addressing an important barrier in rehabilitation; and (d) enhances functional recovery through precise, feedback-driven exercises. When viewed collectively, studies providing evidence of AR in patient care and rehabilitation suggest that this technology contributes to a paradigm shift from therapy-centered to patient-centered care. Rather than replacing clinical expertise, AR extends it, embedding motivation, feedback, and guidance directly into the patient's settings.

In a 2020 study, LaPiana et al. [41] assessed the acceptability and effectiveness of a smartphone-based AR game as a means of rehabilitating stroke patients with upper limb motor functional loss [41]. Five participants with upper-limb motor deficits aged 50-70 years following acute ischemic stroke engaged with an AR-based therapeutic gaming program for one week, with up to three additional sessions per participant. Participants completed 23 of 45 possible sessions, primarily due to fatigue,

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which was the main factor for non-engagement. The average number of sessions attempted per participant was 4.6 (SE=1.3) out of a possible nine. User acceptance and experience were assessed using a 16-item acceptability questionnaire, with four out of five participants (80%) completing this process. Results obtained provided strong indicators in terms of participant motivation with a mean ranking of 4.25 (95% CI: 3.31-5.19) regarding following through with sessions, interest in pursuing more game-based therapeutic programs at 3.75 (95% CI: 2.81-4.69), willingness to pursue more in terms of session availability at 3.50 (95% CI: 2.93-4.07), and motivation in terms of pursuing other forms of rehabilitation at 3.25 (95% CI: 2.76-3.74). All experience parameters, including overall experience at 4.00, overall comfort at 4.25, experience of overall enjoyment at 3.25, and all items related to overall experience, significantly surpassed values established through chance ($P \leq .04$). These data provide preliminary yet strongly supporting indications regarding AR-based therapeutic games' overall acceptance, motivation, and tolerability among stroke patients, thereby strongly supporting existing inferences included in this online review concerning AR restoration of overall persistence of rehabilitation and general reconciliation of services.

Held et al. [42] also tested the effectiveness of the AR system in rehabilitating a patient who had gait impairments. They developed the ARISE (Augmented Reality for gait Impairments after Stroke) system, in which we combined a development version of HoloLens 2 smart glasses (Microsoft Corporation) with a sensor-based motion capture system [42]. One person who had mild walking difficulties after a stroke tried two types of therapy: the usual clinical walking tests and a parkour-style course using AR that gave real-time feedback on how they walked. The researchers carefully watched how the person moved, how easy the system was to use, and whether it was safe. When using the AR course, the participant changed their walking style compared to standard therapy, showing they could adapt to the new, visually rich environment. The person was able to spot and interact with all the virtual parts of the course and found the ARISE system easy and enjoyable to use. There were no safety problems, though the participant did feel a short burst of excitement during the session. To sum up, this early study shows that adding real-time sights and sounds can help people change the way they walk. This suggests that using AR could make walking and balance therapy more flexible and interesting, moving it beyond the usual clinic setting and opening the door for new technology-based treatments in the future.

In 2022, Cerdán de Las Heras et al. [20] conducted a study aimed to explore perceptions, challenges, and expectations following a tele-rehabilitation intervention using AR glasses (ARG) in patients with recently diagnosed myocardial infarction (MI), chronic obstructive pulmonary disease (COPD), and idiopathic pulmonary fibrosis (IPF). Qualitative research was used to assess the perspectives of patients from Finland and Denmark. Thirteen patients (four MI, two IPF, and seven COPD), including three women and ten men aged 56 to 75 years (mean age 63.3 years), participated. They were divided into one focus group (nine participants) and four interviews (four participants) [20]. Of these, 12 reported positive or added value of ARG and suggested constructive changes to improve their rehabilitation, such as supported feedback based on exercise performance, an easy-to-navigate interface, robust head fixation for exercise, and adjustable screen brightness.

Li [43] conducted a similar study that explored the application value of AR in postoperative rehabilitation training for patients with knee joint injury. Forty patients who underwent knee joint surgery participated in this study and were randomly divided into two groups, a control group and an experimental group, with 20 participants each [43]. This comparative study assessed the AR-based rehabilitation group against the traditionally rehabilitated group using clinical, functional, and radiographic outcomes. Compared to the control group at six weeks following treatment, the AR group displayed improved functional outcomes with a higher mean HSS of 85.46 ± 3.21 compared to the control group value of 82.88 ± 3.07 ($P < 0.05$) at six weeks, and this improved functional outcome was maintained at the three-month endpoint with a mean HSS of 93.21 ± 4.33 for the AR group compared to the control group mean of 89.96 ± 3.76 ($P < 0.05$). Pain alleviation was also greater with the AR group with significantly lower scores at VAS at 7 days post-surgery at a mean of 3.81 ± 0.48 for the AR group compared to the control group mean of 5.06 ± 0.66 ($P < 0.05$) and at the 14 days post-surgery mark with a mean value of 2.03 ± 0.45 for the AR group compared to the control group mean value of 3.61 ± 0.63 at the two-time points assessed for VAS scores ($P < 0.05$). In further comparisons involving outcomes from the AR group and the control group for time taken on full weight-bearing and the time to return to work following injury, amputation, resection, and subsequent rehabilitation, the AR group demonstrated a statistically significant improvement at both time points. Overall, the findings showed that AR-based rehabilitation improves postoperative pain control, enhances functional recovery, and supports earlier reintegration into daily activities following knee joint injury.

Other studies in this review that have suggested AR helps in treatment, education & training, and patient care and rehabilitation include: (i) Pruszyńska et al. [44] examining effects of applying AR in remote rehabilitation of patients suffering from multiple sclerosis; (ii) Wang et al. [45] balance rehabilitation system for Parkinson's disease patients based on AR: (iii) Lee et al. [46] effects of the home-based exercise program with an AR system on balance in patients with stroke; (iv) Pieczyńska et al. [47] rehabilitation exercises supported by monitor-AR for patients with high-grade glioma undergoing radiotherapy; Rebol et al. [39] mixed reality communication for medical procedures; Alhumaidi, et al. [48] perceptions of doctors in Saudi Arabia toward VR and AR applications in healthcare; Álvarez-Nieto et al. [49] the effectiveness of scenario-based learning and AR for nursing students' attitudes and awareness toward climate change and sustainability. Moro et al. [50] HoloLens and mobile AR in medical and health science education; and Nekar et al. [51] improvements of physical activity performance and motivation in adult men through an augmented reality approach.

6. Conclusion and Future Directions

This systematic review consolidates findings from 41 studies published in 2020 and 2025, evaluating the application of Augmented Reality (AR) in healthcare and its impact on clinical outcomes and performance. Overall, the results emphasize AR's transition from experimental to clinical use, highlighting its implications and effects in medical practice.

In every domain of outcomes, AR-based interventions helped improve recovery, increase learner confidence, enhance patient engagement, and improve efficiency. Although there were no uniform improvements in primary clinical success rates, there were consistent improvements in secondary endpoints, including reduced completion time, ease of performance, and patient and learner satisfaction. Most significantly, the AR-based intervention demonstrated a favorable safety profile, with adverse events rare, mild, transient, and without evidence of serious harm.

From a workflow perspective, AR demonstrated potential to improve clinical workflows by optimizing spatial orientation, minimizing cognitive load, and facilitating standardized tasks. These attributes show AR's potential to enhance efficiency in training and healthcare delivery. However, scalability challenges due to implementation costs and technological complexity remain.

While future studies should progress from feasibility studies to full-powered clinical trials, increasing focus on health-economic analyses and integrating AR into existing clinical infrastructures would be valuable. This is critical for establishing the long-term value of AR and ensuring its integration into healthcare practice as a valuable tool.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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