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A systematic review insights on integrating augmented reality into surgical training & clinical practice surgery

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ABSTRACT

Augmented Reality (AR) is increasingly recognized as a key enabler of future healthcare innovation, particularly in advancing medical education, clinical training, and surgical procedures. This study presents a Systematic Literature Review (SLR) of AR integration in the medical domain, analysing 62 peer-reviewed articles from the Scopus database. The review explores five aspects: interaction devices, AR functions, AR impacts, solution validation methods, and medical implementation stages. Results reveal that appearance is the most dominant AR function (41%), followed by procedural guidance in both training and real clinical settings (24% each). Head-Mounted Displays (HMDs) are the most widely used interaction device (67%), offering immersive and real-time visual support. AR integration is most prevalent during the intra-operative phase (44%). Reported AR impacts commonly span multiple dimensions, including enhanced accuracy, effectiveness, efficiency, error, and educational outcomes (37%). Validation methods are primarily based on statistical analysis (40%). This review underscores AR's growing role in transforming healthcare delivery, medical education, and highlights opportunities for future development in multifunctional AR systems, cost-benefit analyses, and expansion into additional medical subspecialties.

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1. INTRODUCTION

The integration of advanced technologies has catalysed transformation across healthcare systems, enabling new forms of diagnosis, training, and intervention. Among these, Augmented Reality (AR) stands out as an emerging innovation that blends virtual elements into real-world environments in real time. AR offers the potential to enhance operational efficiency, optimize decision-making, and improve human–technology interaction within medical workflows—key priorities from an industrial engineering standpoint. AR facilitates real-time visualization of patient-specific anatomy, improves surgical navigation, and supports simulation-based training for healthcare professionals [1], [2].

In medical education, the ability to understand complex anatomical structures is critical but often limited by conventional learning tools. AR addresses this gap through immersive 3D representations, allowing learners to interact with anatomical models in ways that improve spatial awareness and knowledge retention

[3]. Similarly, in surgical and diagnostic applications, AR has been shown to improve procedural planning, reduce errors, and support minimally invasive interventions by overlaying real-time data onto the surgical field [4], [5].

From a system engineering perspective, the integration of AR into healthcare processes represents a critical aspect of digital transformation, aimed at reducing process variability, enhancing standardization, and improving overall system reliability. AR technologies—such as Head-Mounted Displays (HMDs), handheld AR interfaces, and patient-specific imaging overlays—are increasingly viewed not merely as visualization tools but as integral components of smart healthcare ecosystems that support data-driven decision-making and workflow optimization [6], [7].

Their adoption, however, introduces several implementation challenges. These include issues of interoperability with existing hospital information systems, high initial costs, and limited return-on-investment evaluations, lack of robust clinical validation, and resistance to workflow restructuring—all of which are central concerns within the domains of industrial engineering, operations research, and health systems management [8], [9]. Addressing these challenges requires a multidisciplinary approach that integrates engineering design, usability studies, cost–benefit modelling, and stakeholder engagement to ensure the successful and sustainable deployment of AR technologies in clinical environments.

Although research on AR in healthcare has expanded rapidly, human factors and user-centred design are crucial for the successful adoption of new medical technologies. Recent work in digital health has shown how structured engineering methods can be used to translate user requirements into technical specifications, for example, through the use of Quality Function Deployment (QFD) in the development of an IoT-based Augmentative and Alternative Communication device for stroke patients. Comprehensive analyses that synthesize findings across applications and disciplines remain limited [10]. Consequently, the full potential of AR to drive healthcare innovation, particularly in optimising system performance and improving patient outcomes, has yet to be systematically evaluated [11]. This study conducts a systematic literature review (SLR) to examine trends, applications, and implementation challenges in AR adoption across healthcare domains. In this review, "medical education" denotes surgical and procedure-oriented training, and "clinical practice" denotes AR use in real patient care (preoperative planning and intraoperative guidance). Accordingly, we focus on surgery-related applications and do not cover non-surgical medical domains. The review aims to guide future research and practice by identifying knowledge gaps, highlighting enabling technologies, and providing interdisciplinary insights that foster healthcare innovation. To ensure conceptual clarity and a coherent scope for this review, it is important to first define how key terms are used and to delimit the specific contexts of AR adoption considered in this study.

2. MATERIALS AND METHODS

In this study, an SLR approach has been employed to investigate the AR integration in the medical domain and identify emerging trends, applications, and implementation challenges. This selected SLR pathway postulates a structured and replicable framework for fusing existing research, enabling a comprehensive coverage and minimizing bias. The SLR offers a more meticulous process to examine evidence, identify recurring patterns, and highlight critical research gaps in comparison to narrative or scoping reviews. Particularly, this review aims to consolidate knowledge on the AR usage in diverse medical subfields, emphasizing interaction devices, functional roles, impacts, validation methods, and their implications for clinical practice and education. Furthermore, providing structured insights into the potential directions of AR adoption in healthcare systems. The review process comprised four main stages: planning, scope definition, reference search strategy, and journal selection and filtering, as summarized below. To clarify the research focus, this study addresses the following question: "How is integration of Augmented Reality (AR) into the medical field, and what are the key interaction devices, functions, impacts, and implementation challenges in advancing healthcare innovation?"

2.1. Planning Stage

This stage involved selecting data sources, tools, and inclusion criteria. The Scopus database was selected due to its comprehensive multidisciplinary coverage and reliable indexing of peer-reviewed literature, making it a common choice for systematic reviews [12], [13]. References were managed using Mendeley, which supports efficient reference organization and metadata management, especially in collaborative and review-based research [14]. The synthesis and reporting stages were carried out using Microsoft Word, a standard platform for scholarly documentation.

2.2. Scope Definition

To ensure the review's relevance to both academic and practical stakeholders, the scope was defined to include five key variables related to AR applications in healthcare:

2.2.1. Interaction Device

This refers to the hardware used to deliver AR experiences in medical contexts. Several types of AR devices are commonly employed:

a. Head-Mounted Device (HMD) is a wearable device that presents augmented elements directly in front of the user's eyes.
b. Hand-Held Device (HHD) is a portable device, such as smartphones, tablets, or AR kits, used to display AR content.
c. Monitor-based is a virtual element that is displayed on a computer monitor as the main interface.
d. Projector-based system is a projector that is used to display virtual content directly on real-world surfaces.

2.2.2. AR Function

This refers to the technological capabilities of AR systems in enhancing user understanding, operational efficiency, and experiential engagement. These functions span various practical applications in healthcare, as detailed below:

a. Guidance is the AR function as a visual aid that provides step-by-step guidance in performing medical procedures, particularly in surgical procedures. AR displays visual elements such as guidelines, anatomical overlays, or surgical tool paths in real-time on the patient's body. There are two types of guidance used, namely:
    1) Guidance in real procedure: Guidance used in the process of direct action on real patients.
    2) Guidance in training: Guidance used in the training process for medical students or medical personnel, where the procedure is simulated virtually to resemble real conditions.
b. Appearance refers to AR's ability to display anatomical structures or medical models in a realistic and interactive 3D visual format. This visualization is useful for understanding the shape of organs, the position of internal structures, and procedure planning.
c. Collaboration refers to the ability of medical teams to work from different locations with the same AR visual view.
d. Multiple refers to AR systems that simultaneously provide more than one functional capability within a single application, such as combining appearance with procedural guidance, training support, or collaborative features. In these studies, AR is not limited to a single task but is designed as a multi-purpose tool that integrates visualization, instruction, and interaction in a unified workflow.

2.2.3. AR Impact

This refers to the effect or consequence resulting from the application of AR technology in the medical field, both in direct medical procedures and in the context of medical education or training. This impact encompasses various aspects related to improving the quality of medical services, work efficiency, patient safety, and overall medical education effectiveness. To facilitate understanding of the impact of AR in this journal, the following is an explanation of each classification.

a. Accuracy refers to the ability of AR technology to improve the accuracy of medical procedures, particularly in procedural navigation, instrument placement, and interpretation of patient anatomy using real-time visual support. AR helps medical personnel reduce technical errors and improve the precision of procedures and clinical diagnoses during interventions.
b. Effectiveness refers to the extent to which AR users support the achievement of optimal clinical or educational outcomes. This includes procedural success, improved quality of care, and the achievement of medical training objectives, such as skill and concept mastery by doctors and medical personnel in an efficient manner.

c. Efficiency describes the impact of AR in reducing the time required to complete medical procedures or training. By using AR, clinical processes can be performed quickly, using optimal resources, thereby increasing work productivity in clinical settings.
d. Error refers to how AR can help reduce mistakes during the execution of medical procedure steps, such as incorrect incisions (error of determining the location, direction, or depth of an incision), incorrect positioning of instruments, or incorrect sequence of actions. This is particularly relevant in the execution of medical procedures using AR.
e. Education refers to the impact of AR in enhancing clinical learning and training processes, particularly in improving student motivation, anatomical understanding, procedural skill mastery, and retention of medical information.
f. Multiple refers to the application of AR that has multiple positive impacts simultaneously in a single study. This occurs when AR is not limited to a single aspect but simultaneously provides benefits in terms of accuracy, effectiveness, efficiency, error, and education within a single medical scenario application.

2.2.4. Solution Validation

This refers to the process of assessing the effectiveness, efficiency, and reliability of AR technologies in fulfilling their intended purposes. In the medical context, validation includes technical testing, user feedback, and evaluation of specific performance indicators such as safety, usability, and clinical outcomes. The solution validation includes:

a. Statistical analysis refers to a quantitative approach based on numerical data processing, used to evaluate the performance of AR technology through indicators such as navigation accuracy, procedural effectiveness, response time, and learning outcomes. Data are analyzed using descriptive or inferential statistical methods to demonstrate the effectiveness of the system.
b. Comparative evaluation refers to a comparison between AR technology and conventional methods or alternative technologies. The aim is to assess the extent to which AR is superior in terms of clinical outcomes, work efficiency, and user experience.
c. Laboratory testing refers to the validation conducted in a simulated or controlled laboratory environment before the AR system is implemented in a real clinical setting. To assess the initial performance of the system, including visual accuracy, processing speed, and responsiveness to users.
d. Field testing refers to the direct evaluation of the AR system conducted in operating rooms, clinics, or realistic medical simulations. It aims to assess AR performance under real clinical conditions, including user comfort, system integration, and overall impact.

2.2.5. Medical Implementation

This refers to the specific clinical or educational context in which AR is applied, particularly in supporting surgeons and medical staff with real-time visual guidance to improve precision, efficiency, and outcomes. AR can be applied in the following domains:

a. Intra-operative is a real-time use of AR during surgeries or medical procedures to provide visual guidance and enhance decision-making and precision.
b. Pre-operative is AR for planning, preparation, and simulation of medical procedures before they are carried out on patients.
c. Training is AR-based education and skill development for medical personnel—including doctors, nurses, surgeons, and students—through realistic and interactive training modules.

2.3. Reference Search Strategy

The literature search was conducted exclusively via the Scopus database using the following primary keyword combination: "Augmented Reality" AND "Medical" AND "Surgery". This query was designed to capture studies at the intersection of immersive AR technology and its application in medical and surgical contexts. We used “Augmented Reality” as a mandatory keyword to specifically capture studies on AR, and to avoid including work that focused primarily on other extended reality technologies, such as virtual reality or mixed reality. We added the keyword “Medical” to ensure that the studies selected focused on AR applications in the field of health, rather than on the use of AR in non-medical domains. The last keywords we intentionally included were the keyword “Surgery” in the search query to restrict the review to procedurally and surgically relevant AR applications. As a result, non-surgical AR studies (e.g., in general medical education, rehabilitation, dermatology, or diagnostics) were not captured. This focus was chosen to enable a more coherent and in-depth synthesis of surgery-related AR implementations. The initial search returned a total of 1,485 articles.

2.4. Journal Selection and Filtering

A multi-stage filtering process was applied to ensure the inclusion of high-quality and relevant peer-reviewed articles:

a. Phase I: Filtering by publication year (2019–2024) reduced the results to 858 articles.
b. Phase II: Scopus filters were applied with the following criteria: Document type (Article); Subject area (Medicine, Engineering, Health Professions, Dentistry, Multidisciplinary); Language (English); Access (All Open Access); Publication stage (Final); Source type (Journal); and Keywords (including AR, surgical training, HMD, medical simulation, patient-specific data, clinical practice, and minimal invasive surgery). This step narrowed the dataset to 165 articles. We included only full-length, peer-reviewed journal articles; conference proceedings and other non-journal sources were excluded.
c. Phase III: Manual screening of titles and abstracts to assess topic relevance yielded 81 articles.
d. Phase IV: Full-text analysis of the remaining articles was performed to ensure alignment with the research scope and inclusion criteria, resulting in a final selection of 62 relevant articles used for this systematic review.

The complete selection and screening workflow is illustrated in Figure 1.

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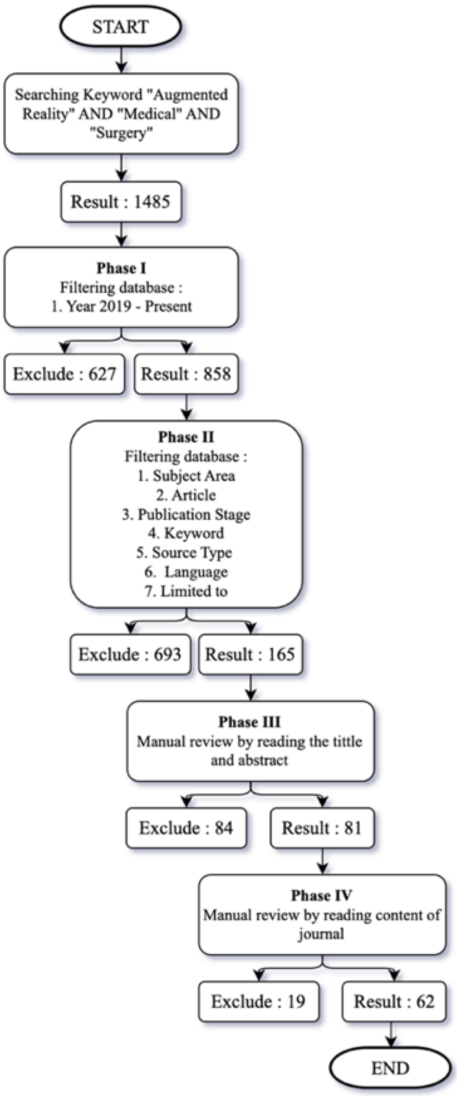

Figure 1. Flowchart of journal selection and screening process

Following the Scopus database search, a manual review was conducted to identify distinguishing elements that were not commonly emphasized in previous literature. This SLR synthesizes and classifies the selected articles based on the defined scope: Interaction Devices, AR Functions, AR Impacts, Solution Validation, and Medical Implementation are summarized in Table 1.

Table 1. Overview of retrieved and classified literature

Ref.	Interaction Device	AR Function	AR Impact	Solution Validation	Medical Implementation
[15]	HMD	Appearance	Accuracy	Comparative evaluation	Pre-operative
[16]	HHD	Guidance in training	Effectiveness	Statistical analysis	Pre-operative
[17]	HMD	Guidance in training	Multiple	Comparative evaluation	Pre-operative
[18]	HMD	Appearance	Error	Comparative evaluation	Pre-operative
[19]	HMD	Appearance	Education	Statistical analysis	Pre-operative
[20]	HHD	Appearance	Multiple	Statistical analysis	Training
[21]	HMD	Appearance	Multiple	Statistical analysis	Training
[22]	Projector	Appearance	Multiple	Statistical analysis	Training
[23]	HMD	Appearance	Multiple	Field testing	Intra-operative
[24]	HMD	Appearance	Accuracy	Field testing	Intra-operative
[25]	Monitor	Appearance	Effectiveness	Laboratory testing	Intra-operative
[26]	HMD	Appearance	Effectiveness	Statistical analysis	Intra-operative
[27]	HMD	Appearance	Error	Laboratory testing	Intra-operative
[28]	HMD	Appearance	Education	Statistical analysis	Training
[29]	Projector	Guidance in real procedure	Error	Laboratory testing	Intra-operative
[30]	HHD	Guidance in training	Education	Laboratory testing	Training
[31]	HMD	Appearance	Efficiency	Statistical analysis	Intra-operative
[32]	Monitor	Guidance in real procedure	Multiple	Statistical analysis	Intra-operative
[33]	HMD	Appearance	Multiple	Comparative evaluation	Intra-operative
[34]	Projector	Appearance	Education	Comparative evaluation	Pre-operative
[35]	HMD	Appearance	Effectiveness	Statistical analysis	Intra-operative
[36]	HMD	Guidance in real procedure	Multiple	Statistical analysis	Intra-operative
[37]	HMD	Appearance	Education	Comparative evaluation	Intra-operative
[38]	HMD	Guidance in training	Effectiveness	Comparative evaluation	Pre-operative
[39]	HMD	Guidance in real procedure	Accuracy	Field testing	Intra-operative
[40]	Monitor	Appearance	Multiple	Laboratory testing	Intra-operative
[41]	HMD	Guidance in real procedure	Error	Field testing	Intra-operative
[42]	HMD	Guidance in training	Effectiveness	Laboratory testing	Pre-operative
[43]	HMD	Guidance in training	Error	Laboratory testing	Pre-operative
[44]	HMD	Guidance in training	Education	Statistical analysis	Training
[45]	HMD	Multiple	Effectiveness	Field testing	Pre-operative
[46]	HMD	Guidance in training	Multiple	Laboratory testing	Training
[47]	Monitor	Appearance	Effectiveness	Field testing	Intra-operative
[48]	HMD	Guidance in real procedure	Efficiency	Laboratory testing	Intra-operative
[49]	HMD	Guidance in training	Education	Laboratory testing	Training
[50]	HMD	Guidance in training	Education	Statistical analysis	Training
[51]	HMD & HHD	Appearance	Education	Comparative evaluation	Training
[52]	HHD	Guidance in training	Effectiveness	Field testing	Pre-operative

Ref.	Interaction Device	AR Function	AR Impact	Solution Validation	Medical Implementation
[53]	HMD	Guidance in real procedure	Multiple	Laboratory testing	Intra-operative
[54]	HMD	Guidance in real procedure	Efficiency	Statistical analysis	Intra-operative
[55]	HHD	Multiple	Education	Statistical analysis	Training
[56]	Projector	Appearance	Multiple	Statistical analysis	Pre-operative
[57]	HMD	Guidance in real procedure	Accuracy	Statistical analysis	Intra-operative
[58]	HMD	Guidance in real procedure	Multiple	Comparative evaluation	Intra-operative
[59]	HMD	Appearance	Multiple	Statistical analysis	Pre-operative
[60]	HMD	Multiple	Effectiveness	Laboratory testing	Pre-operative
[61]	HHD	Guidance in real procedure	Multiple	Comparative evaluation	Intra-operative
[62]	Projector	Multiple	Error	Comparative evaluation	Pre-operative
[63]	HMD	Guidance in real procedure	Accuracy	Comparative evaluation	Intra-operative
[64]	HMD	Appearance	Multiple	Statistical analysis	Intra-operative
[65]	Projector	Guidance in training	Effectiveness	Comparative evaluation	Pre-operative
[66]	HMD	Guidance in training	Accuracy	Statistical analysis	Intra-operative
[67]	HMD	Appearance	Multiple	Statistical analysis	Pre-operative
[68]	HMD	Guidance in training	Multiple	Statistical analysis	Pre-operative
[69]	HHD	Guidance in training	Multiple	Statistical analysis	Pre-operative
[70]	HMD	Guidance in training	Multiple	Statistical analysis	Intra-operative
[71]	HMD	Multiple	Effectiveness	Comparative evaluation	Training
[72]	HMD	Guidance in training	Effectiveness	Comparative evaluation	Training
[73]	Monitor	Multiple	Multiple	Comparative evaluation	Pre-operative
[74]	HMD	Appearance	Accuracy	Comparative evaluation	Intra-operative
[75]	Projector	Multiple	Multiple	Comparative evaluation	Intra-operative

3. RESULTS

3.1. Statistical Summary

Research on AR applications in medicine showed a consistent rise in published articles between 2019 and 2024, particularly during the period from 2019 to 2022, based on the distribution. Publications rose, indicating an upward trajectory, starting with 6 articles in 2019 to 9 articles in 2020, 13 articles in 2021, and peaking at 14 articles in 2022. This steady increase was driven by several important factors, including significant advancements in AR technology, especially in appearance and surgical navigation, which have become more precise and accessible for medical professionals during patient procedures. Additionally, the urgent need for innovative solutions to enhance the safety and efficiency of medical procedures, along with growing awareness of immersive technology in medical education, further fueled research interest in this field. Another significant contributing factor is, COVID-19 pandemic, which has created a need for contactless medical training technology, thereby accelerating the adoption of AR in both clinical and educational contexts. After reaching its peak in 2022, the number of publications saw a slight decline and remained relatively stable in 2023 and 2024, with 10 articles each year, indicating a transition from the exploratory phase toward a deeper phase of evaluation and practical implementation of AR applications in medical practice. The year-by-year distribution of scientific publications is illustrated in Figure 2.

3.2. Interactive device

Figure 3 shows that head-mounted displays (HMDs) dominate AR implementations in medicine, accounting for 67% of the reviewed studies. HMDs are preferred because they provide hands-free, real-time visualization directly within the user's field of view, allowing surgeons and medical staff to access anatomical

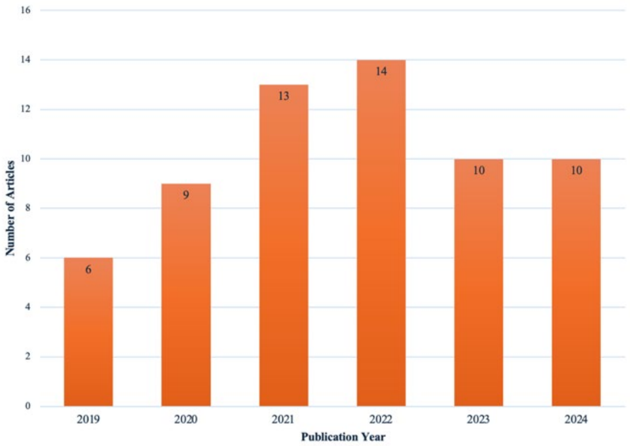

Figure 2. Distribution of published articles by year

information, navigation cues, and other critical data without looking away from the operative or working area. Handheld devices (HHDs), such as smartphones and tablets, represent 11% of the applications and are mainly used in training or consultation scenarios where portability and ease of access are more important than full immersion. Monitor-based AR systems (11%) are typically employed when additional information can be displayed on a separate screen without the need for wearable devices, for example, in certain diagnostic or image-guided procedures. Projector-based AR accounts for 9% of the studies and is particularly useful in collaborative settings, as it can project information directly onto physical surfaces so that the whole team shares the same augmented view. A small proportion of studies (2%) combine HMDs and HHDs within the same system, indicating early efforts toward hybrid interaction schemes, although such solutions remain relatively rare. Overall, these findings suggest that current medical AR research prioritizes immersive, hands-free visualization through HMDs, while other devices serve more targeted or context-specific roles.

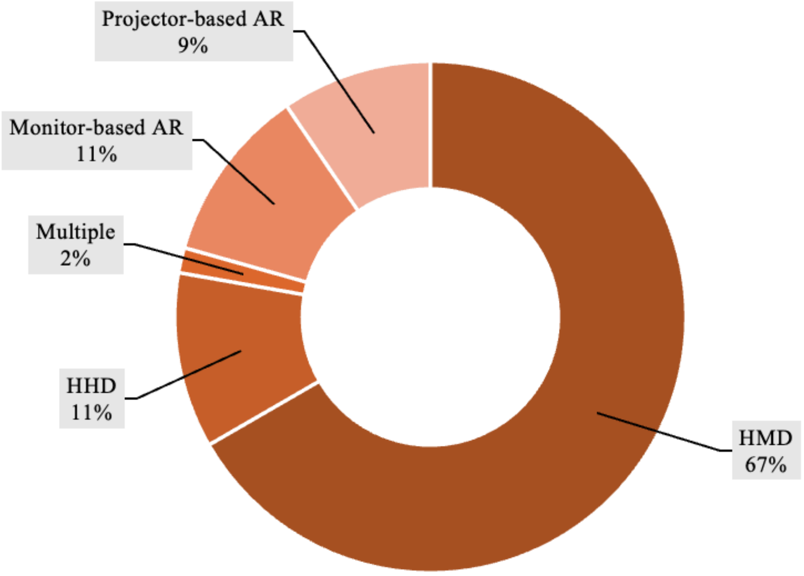

Figure 3. Distribution of different AR interaction devices

The dominance stems from their ability to offer immersive real-time visualization directly in the user's field of view, allowing surgeons or medical personnel to receive visual guidance without diverting their attention from the clinical area. The primary advantage of HMD devices lies in their ability to present patient data, such as anatomical structures in 3D, diagnostic images, surgical pathways, and other critical information, seamlessly integrated into the user's visual field. The use of HMDs (in Figure 4a) has significantly improved the accuracy of medical procedures, such as ultrasound-guided interventions, thereby supporting faster and more precise decision-making in complex clinical environments [36].

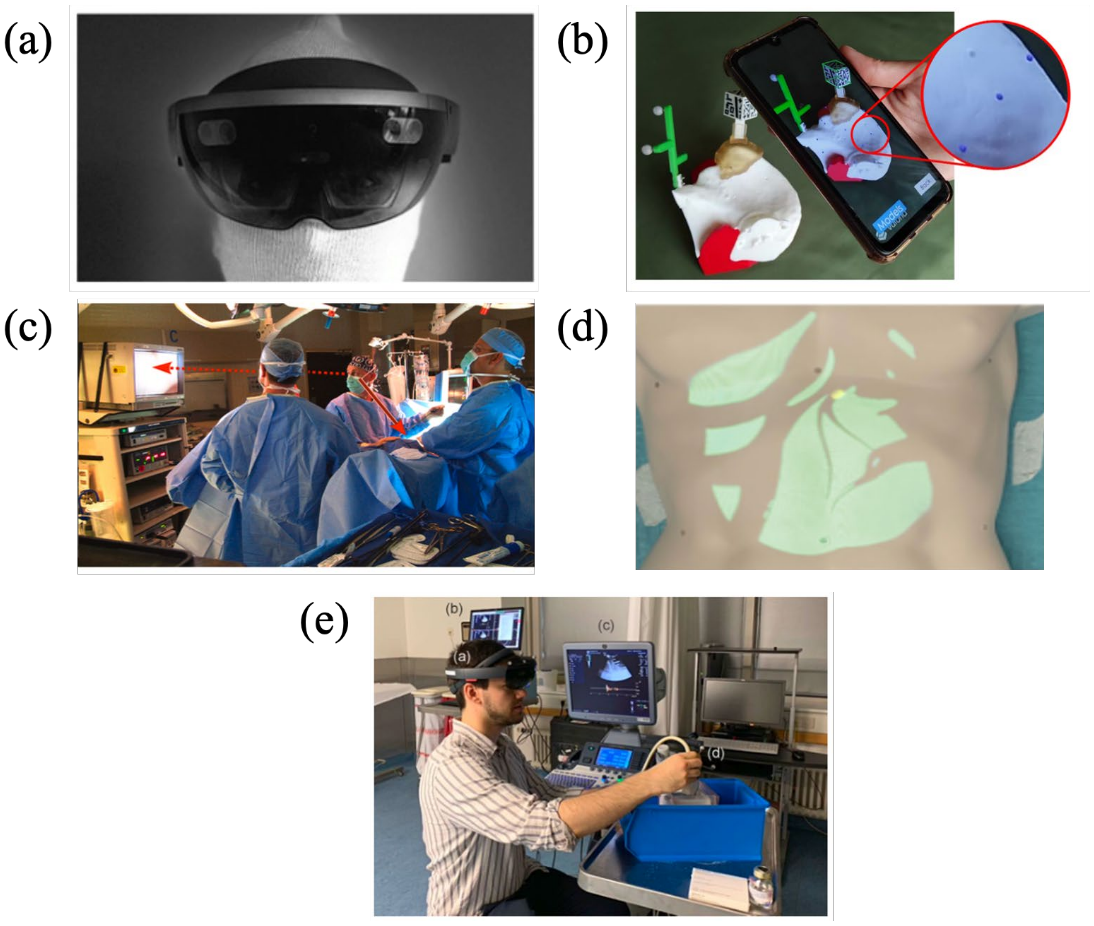

Figure 4. (a) Head Mounted Display (HMD) [17]; (b) HandHeld Display (HHD) [16]; (c) Monitor-based AR [37]; (d) Projector-based AR [22]; (e) Multiple [24]

The second most widely used interaction device is HHD, accounting for 11% of the market in medical AR applications, typically used in tablets or smartphones, enabling flexible, portable platforms for interacting with virtual elements. These devices are particularly effective for training or medical consultations that do not require direct hands-on procedural actions. For instance, A study highlights that the usage of HHDs (in Figure 4b) enables medical students and healthcare professionals to conveniently access virtual anatomical models and medical procedure guidelines, thereby enhancing clinical understanding and operability in training environments [16]. Simultaneously, monitor-based AR devices represent 11% usage of reported applications, typically employed in scenarios where users do not require full immersion and only additional information is displayed on a separate monitor screen. For example, diagnostic or medical procedures (in Figure 4c) require brief additional references and are not highly immersive. Prior research demonstrated their effectiveness, which allows doctors to see navigation guides directly within their field of view, thereby improving visual precision and intra-operative work efficiency [22]. Further, projector-based AR devices account for 9%, primarily used to project medical visuals directly onto real objects or physical surfaces. These devices are highly valuable in collaborative clinical contexts, as they enable the entire surgical team to share a clear, accurate, and real-time visualization of patient anatomy and procedural navigation. A study indicated that projector-based AR (in Figure 4d) is effective in minimally invasive procedures, allowing multidisciplinary teams to coordinate seamlessly through shared appearance projected directly onto the surgical site [22].

In contrast, the use of combined HMD and HHD devices (in Figure 4e) accounts for the least 2% of applications, which are dominant in specific contexts that require diverse interactions, either through wearable or portable devices, to maximize flexibility. However, the adoption is still limited due to the complexity and limitations of integration between devices; nonetheless, emerging research has begun to explore the potential benefits of this hybrid approach. Overall, the dominance of HMD devices indicates that most current medical AR applications prioritize immersive experiences that enable real-time guidance and visualization in rapidly changing clinical environments over time.

Figure 5 classifies AR usage into four main functional categories: appearance, guidance in real procedures, guidance in training, and multiple. Appearance is the most common function (41%), indicating that many systems are designed primarily to provide realistic, interactive 3D visualization of anatomical structures or medical models. This function supports users in understanding complex spatial relationships and planning procedures, for example, in tumor mapping, maxillofacial reconstruction, or spinal surgery simulations, as shown in Figure 6. Guidance in real procedures and guidance in training each account for 24% of the applications. In real procedures, AR provides intra-operative overlays, incision or instrument trajectories, and real-time navigation aids directly on the patient or in the operative field, helping to improve precision and reduce errors. In training contexts, AR delivers step-by-step instructions or performance feedback during simulated tasks, enabling students and residents to practice procedure-oriented skills in realistic but controlled environments (in Figure 7). The remaining 11% of systems fall into the "Multiple" category, where AR combines more than one function, such as integrating anatomical visualization with procedural guidance or collaborative features within a single application. This pattern suggests that while visualization remains the dominant entry point for AR in medicine, there is growing interest in multi-functional solutions that more closely support real clinical and educational workflows. The advantage of using AR in this scenario is its ability to provide direct visual references without requiring the operator to look away from the operating field or at a separate screen, thereby reducing distractions and improving the efficiency and accuracy of clinical procedures.

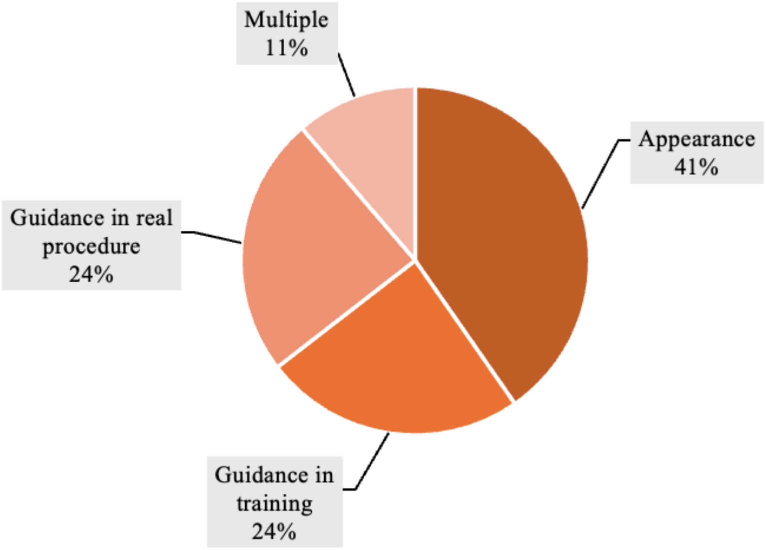

Figure 5. AR function classification

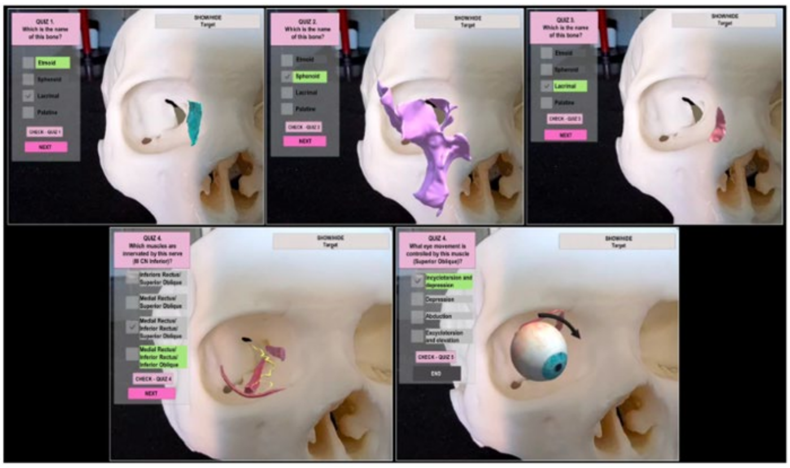

Figure 6. Appearance [30]

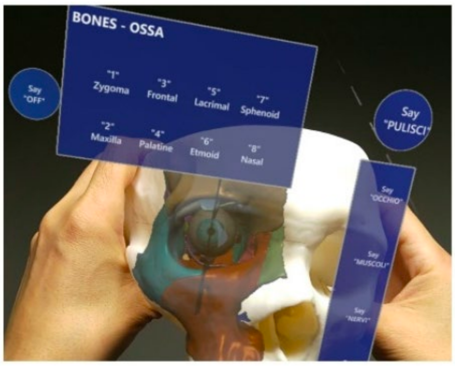

Figure 7. Guidance in training [51]

Meanwhile, the use of AR in medical training or education also demonstrates significant contributions. AR is used as an aid in self-directed training for medical students or surgical residents for independent practice, thereby reducing reliance on direct supervision from instructors. Through AR, trainees can practice procedures such as wound suturing, ventricular drain placement, or instrument manipulation in orthopedic surgery, receiving immediate feedback on errors and the accuracy of their movements. Several studies have shown that AR-based training can improve learners' confidence, technical skills, and spatial understanding better than traditional methods such as instructional videos or physical models alone. Interestingly, the last category accounts for only 11% of the overall distribution for multiple device technology. This indicates that there are still a few AR applications that combine more than one function, such as integrating visualization simulations, procedural training, and clinical guidance into a single system. Yet, the development of such systems has great potential in the context of teaching hospitals or medical simulation centers to improve efficiency and flexibility. A notable example of an AR system developed for kidney and prostate cancer, used in three phases: visualizing patient anatomical models for education, pre-operative planning by doctors, and intra-operative navigation during the procedure. Detailed information on multiple uses is available in Table 2.

Table 2. Multiple AR functions

No	Combination	Number of Articles
1	Guidance in training & Collaboration	1
2	Appearance & Collaboration	3
3	Appearance & Guidance in training	3
	TOTAL	7

Overall, this pie chart provides a clear picture of AR technology's current utilization in the medical field. The dominance of visualization aspects indicates that AR is still in the early stages of adoption, where visual advantages are the primary focus of development and utilization. However, with advancements in hardware such as HMDs and improvements in motion tracking precision, as well as the integration of medical data like CT or MRI scans, the trend in AR usage will increasingly shift toward more active and interactive applications, both in medical education and in direct clinical procedures. Therefore, the future challenges are not only about improving accuracy and user comfort but also about designing AR systems that are multifunctional, cost-efficient, and easily integrated into hospital workflows or medical education institutions. As a result, AR promotes a significant opportunity to become an integral part of the future medical technology ecosystem. In addition to these predominantly visualization and guidance-oriented uses, a smaller but important subset of studies explores how AR can mediate collaboration between clinicians across different locations.

Beyond appearance and guidance, only a small subset of studies explicitly implemented AR for collaborative purposes, for example, in telementoring, remote assistance, or shared decision-making between geographically distributed teams. In these works, AR was used to share a common augmented view of the operative field or anatomical model, enabling experts and trainees to discuss procedures in real time across different locations. However, even in collaboration-focused studies, ethical aspects such as patient privacy, secure transmission of clinical images, or consent for remote observation were rarely discussed in a systematic way. This suggests that while technical collaboration features are emerging, their organizational and ethical implications remain largely underreported in the current literature.

As shown in Figure 8, most studies assess AR using more than one outcome dimension. The "Multiple" impact category is the largest (37%), followed by effectiveness (21%), education (16%), accuracy (11%), error (10%), and efficiency (5%). The dominance of the Multiple category reflects the fact that AR interventions in medical contexts rarely produce isolated effects. As summarized in Table 3, procedure-oriented studies often combine accuracy and error reduction, or accuracy and efficiency, to capture both the precision and safety of AR-guided interventions. Training and educational studies frequently evaluate effectiveness together with education-related outcomes such as knowledge gain, confidence, or spatial understanding. In some cases, effectiveness is also examined alongside efficiency, for example, by measuring task performance and time savings in the same experiment. These patterns indicate that AR is typically evaluated holistically, with improvements in visualization and guidance being linked to concurrent gains in technical performance, safety, and learning outcomes, while efficiency is addressed less frequently as a stand-alone focus. For example, in surgical training, the effectiveness of AR was compared to instructional videos was evaluated based on participants' ability to perform suturing correctly and efficiently after training was evaluated [36].

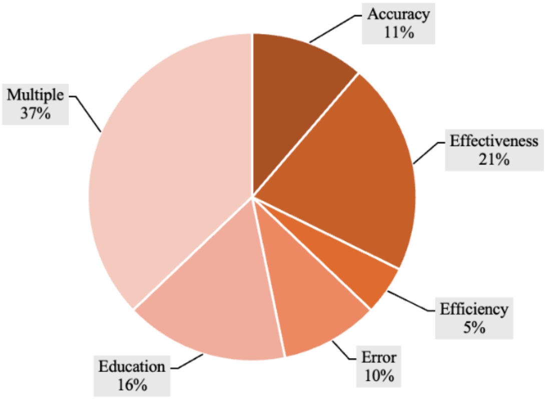

Figure 8. AR Impact classification

The education category also has a substantial share of 16%, indicating that the use of AR in the context of medical education, whether for students, medical personnel, or specialists, could be a significant focus in evaluations. AR technology has proven to support stronger and more interactive visual-spatial learning, as demonstrated in various procedural simulations and AR-based clinical training that enhance participants' understanding of anatomy and technical skills.

Table 3. Multiple AR impacts

No.	Combining AR Impact	Number of Articles
1	Accuracy & Effectiveness	4
2	Accuracy & Efficiency	3
3	Accuracy & Error	3
4	Effectiveness & Efficiency	7
5	Effectiveness & Education	3
6	Effectiveness & Error	1
7	Efficiency & Error	2
	TOTAL	23

Meanwhile, accuracy of 11% and error 10% are also important components in the evaluation of AR systems. Accuracy plays a crucial role, especially in procedures that require high precision, such as spinal screw placement, tumor resection, or minimally invasive biopsy. Error, on the other hand, serves as a negative indicator that must be minimized through AR-based guidance. Some studies indicate that AR usage can significantly reduce errors in tool placement or intervention pathways by providing real-time visualization of targets and instruments.

The smallest proportion, 5%, corresponds to efficiency, which refers to the optimization of time and resources through the use of AR. Despite its importance, this aspect does not seem to be the main focus in most studies and remains unexplored. In clinical practice, however, time efficiency is valuable in the context of surgery duration, hospital workflow, and training efficiency. In this impact classification, efficiency is the least frequently evaluated outcome; only 5% of the studies reviewed reported efficiency as an independent impact category, which mainly refers to the optimization of time or resources in medical procedures. In contrast, effectiveness, education, accuracy, and error reduction were the main focus in 21%, 16%, 11%, and 10% of studies, respectively, while 37% of studies fell into the 'Multiple' category (Figure 8). Efficiency was also embedded within this 'Multiple' category (e.g., Accuracy & Efficiency in 3 articles, Effectiveness & Efficiency in 7 articles, Efficiency & Error in 2 articles, see Table 3), bringing the overall efficiency combined to 25%. This shows that efficiency is not completely ignored in the literature, but it is rarely the main focus in AR evaluation. Instead, efficiency-related measures are generally treated as secondary results that complement dominant dimensions such as effectiveness, accuracy, and educational benefits.

Some early studies show the potential of AR in speeding up decision-making and reducing training time, but limited quantitative data. Overall, the pie chart in Figure 8 shows that approaches to evaluating AR technology in the medical field are diverse but tend to lean toward a multidimensional approach. The 'Multiple' impact category includes studies that assess more than one outcome dimension at the same time, for example, combinations such as Accuracy & Effectiveness, Accuracy & Efficiency, Effectiveness & Efficiency, or Effectiveness & Education. Rather than isolating a single metric, these studies evaluate AR holistically by examining how it simultaneously influences technical performance (e.g., accuracy, error reduction), educational outcomes, and, in some cases, efficiency-related measures such as task time. This reflects the fact that AR interventions in medical contexts rarely produce isolated benefits; improvements in guidance and visualization often translate into concurrent gains in safety, learning, and procedural performance.

Figure 9 shows that statistical analysis is the most frequently used validation method (40%), followed by comparative evaluation (29%), laboratory testing (20%), and field testing (11%). Statistical analysis is typically applied to quantify differences in performance metrics such as navigation accuracy, task completion time, or learning outcomes between AR and control conditions. Comparative evaluations directly contrast AR with conventional techniques (e.g., fluoroscopy, standard imaging, or video-based training) to assess relative advantages in accuracy, efficiency, or user performance. Laboratory testing is mainly conducted in controlled environments using phantoms, dummies, or simulated tasks to examine the technical feasibility and baseline usability of AR systems before clinical deployment. Field testing, although less common, evaluates AR under real or near-real clinical conditions, such as operating rooms or authentic training settings. Overall, these validation strategies demonstrate an emphasis on quantitative performance assessment, with relatively fewer studies examining AR in real-world environments. Overall, this pictorial representation shows that evaluative approaches to AR technology usage are still dominated by statistical and laboratory comparison methods, with field testing remaining relatively limited. Going forward, to increase the relevance and translation of research findings into clinical practice, field testing and longitudinal studies may need to be increased. This is important to ensure that the statistically proven benefits of AR can also be replicated and have a real impact in real-world field settings. Although statistical analysis and laboratory-based evaluations dominate current AR validation approaches, these methods present notable limitations. Most studies rely on short-term, small-sample experiments that evaluate task accuracy or performance time, but seldom measure long-term learning retention, clinical decision-making quality, or patient outcomes. Laboratory simulations often lack ecological validity because they do not capture real operating room complexities such as lighting variations, workflow disruptions, or multi-operator coordination. Comparative evaluations typically benchmark AR against simplified traditional methods, which may underestimate the challenges of integrating AR into existing clinical protocols. Furthermore, only a limited number of studies conduct field testing due to ethical and logistical constraints, resulting in insufficient evidence on AR safety, usability under stress, and interoperability with hospital information systems. These gaps indicate that current validation methods offer an incomplete representation of AR's true clinical effectiveness and reliability.

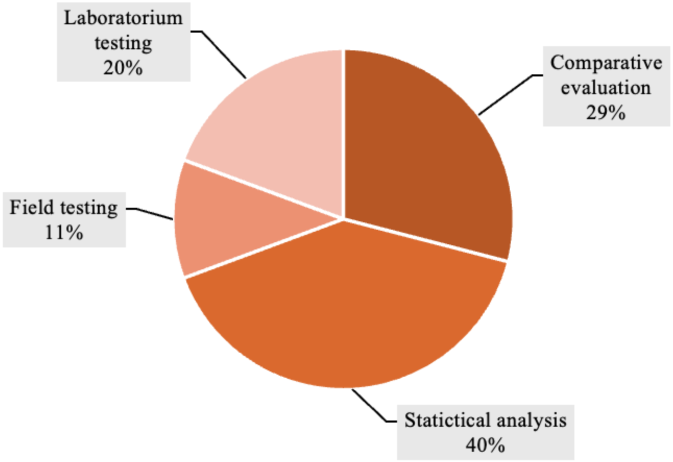

Figure 9. Solution validation classification

In terms of medical implementation, Figure 10, AR is most frequently used in intra-operative settings (44%), followed by pre-operative planning (32%) and training (24%). Intra-operative applications typically provide real-time navigation, instrument guidance, or anatomical overlays during surgery, supporting more precise and safer execution of procedures. Pre-operative implementations focus on visualizing patient-specific anatomy from CT or MRI data and planning surgical strategies, for example, in oncologic resections or reconstructive surgery. Training applications use AR to simulate procedures and anatomical exploration for students and residents, allowing repeated practice without risk to patients. Together, these findings show that AR is currently concentrated in phases of care that are closely linked to surgical decision-making and operative performance, while its use in broader, non-procedural aspects of medical practice remains less prominent. Overall, this pictorial diagram (in Figure 10) illustrates that AR technology is currently most widely utilized in real-world clinical situations, particularly during procedures. However, its contribution to planning and training is equally important. These three stages complement each other and demonstrate that AR plays a comprehensive role in improving the quality of medical services, from preparation, execution, to the development of healthcare professionals' competencies. The continued integration of this technology has the potential to transform medical practice standards toward greater precision, efficiency, and safety.

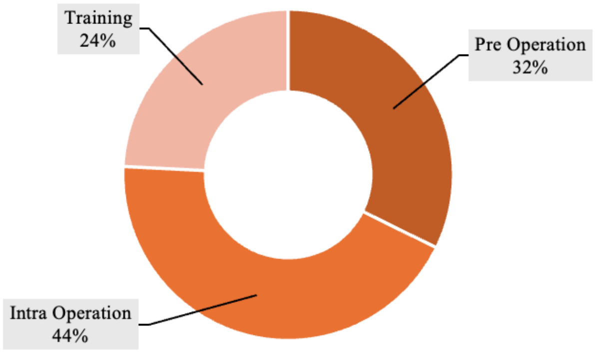

Figure 10. Classification by medical implementation

4. DISCUSSION

The articles studied in this SLR study totaled 62 references with various cases. The majority of references focused on the application of AR technology in the field of surgery, particularly orthopedic surgery, neurosurgery, and urology. The application of AR technology in the medical field provides a new reference that can be used as a guideline or additional technology to facilitate the work of surgeons. The following are the benefits obtained from the application of AR, namely, improved medical education. AR has been proven to assist in the medical education process, and AR can improve medical students' understanding of human anatomy. For example, AR technology enables the visualization of body structures in a 3D format that is far more interactive (in Figure 11a) and easier to understand than using textbooks or 2D images. Based on the research conducted, the use of HMDs provides students with the opportunity to interact directly having more realistic human body models, thereby facilitating their understanding of complex anatomy [76], [77].

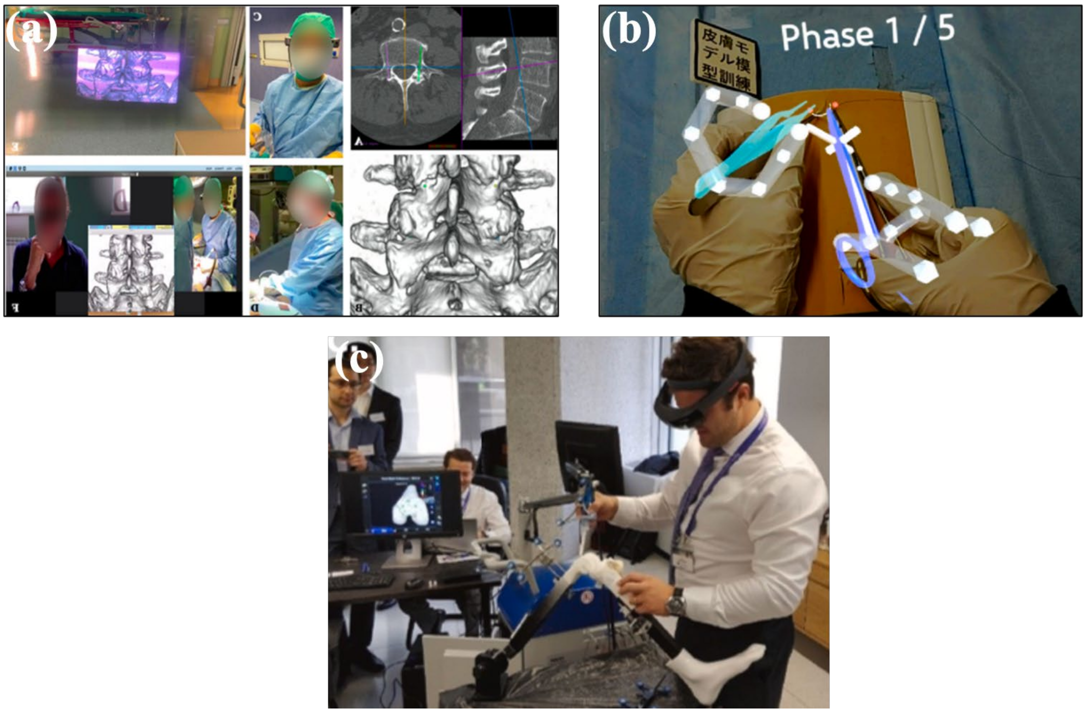

Figure 11. (a) Visualization of intra-operative 3D planning ; (b) Training using an AR system [38]; (c) Visualization of pre-operative [37]

AR offers significant benefits in surgical procedures, particularly in improving accuracy and precision during operations by visualizing the patient's anatomical model directly on the patient's body undergoing the procedure, providing real-time guidance for surgeons. It has been revealed that the use of AR during surgical procedures such as spinal or nerve surgery can assist in planning and executing surgeries more efficiently and safely, thereby reducing the risk of errors and improving the success of the procedure. It is said that training using AR (in Figure 11b) allows medical personnel to practice procedures repeatedly in simulations that closely resemble real-life conditions, thereby helping to develop surgical skills or other medical procedures, especially during the training stage for medical students[28], [36].

AR technology can also support collaboration between geographically separated medical teams. For example, AR enables remote collaboration between medical experts working in different locations (in Figure 11c). This technology can facilitate communication and coordination between doctors, surgeons, and other medical personnel more efficiently through shared visual displays that can assist medical personnel involved in medical decision-making [63]. Additionally, several journals have emphasized the importance of analysis and evaluation to ensure that AR technology can be effectively applied in the medical field. For example, tests have been conducted to evaluate navigation accuracy, improve medical education outcomes, and enhance patient safety during procedures. These observations have important implications for interdisciplinary collaboration and ethical governance in medical AR deployment. These observations have important implications for interdisciplinary collaboration and ethical governance in medical AR. The few collaboration-oriented studies and the near absence of explicit ethical analysis show that current research is still dominated by a technical, performance-focused perspective. In reality, AR systems for telementoring, shared intra-operative views, and surgical training involve multiple stakeholders Similar human-centred approaches have been applied in rehabilitation, such as the design of a therapy wheelchair for stroke survivors using a structured design thinking process that aligns technical features with patient and clinician needs [81] in healthcare (e.g., surgeons, trainees, nurses) and also require input from clinical ethicists and legal advisors to address privacy, data protection, informed consent, and responsibility for AR-influenced decisions. The lack of such interdisciplinary and ethical considerations in the reviewed studies represents a key gap between how AR is currently evaluated and how it should be governed in clinical practice [63], [73]. From an industrial engineering and operations management perspective, this evidence reveals an important misalignment. By contrast, operations and industrial engineering studies in healthcare commonly use system-level indicators and simulation-based approaches to evaluate performance, such as discrete-event simulation of outpatient waiting times and service capacity in hospitals [83], between the motivation stated in the Introduction and the current evaluation practice. Although AR is often promoted as a tool to enhance operational efficiency, workflow optimization, and decision-making in healthcare systems, only a small proportion of the reviewed studies treat efficiency as a primary, stand-alone outcome, and most of them embed efficiency within broader "multiple" impact combinations. Efficiency is typically measured at the task level (e.g., procedure time or task completion speed) rather than through system-level indicators such as patient flow, resource utilization, or process variability. This gap indicates that the potential of AR to support industrial engineering goals in healthcare remains underexplored and highlights the need for future studies to adopt more rigorous, system-oriented efficiency metrics in real clinical environments [35], [68]. While AR offers numerous benefits, there are also challenges that need to be addressed in its implementation.

5. CONCLUSION

This study concludes that AR technology plays a significant role in the transformation of the medical world, particularly in the areas of visualization, procedural guidance, and medical training. In this systematic review, it has been found that appearance is the most dominant AR function, which accounts for 41% of all uses. This function utilizes AR's ability to display the human body structure in an interactive and realistic 3D form, which is very useful in the medical learning and planning process. In addition, the guidance function, both in real procedures and in training, accounted for 24% showing that AR is also widely used as a navigation aid for doctors when performing direct medical procedures or in medical education simulations that resemble real conditions. Although limited, the use of multiple functions or the combination of several AR functions simultaneously was found in 11% of studies, reflecting AR's significant potential for multi-task integration in the future, such as combining visualization simulations, education, and clinical guidance into a single integrated system.

Overall, AR is most commonly used during the intra-operative phase (44%) due to its ability to provide real-time guidance during medical procedures. The most dominant device used is the Head-Mounted Display (HMD) at 67% due to its advantage of displaying information directly in the user's field of view without disrupting their focus on the task at hand. The impact of AR implementation also shows strong results, with 37% of studies reporting multiple impacts such as improved accuracy, effectiveness, efficiency, safety, as well as educational and diagnostic quality. Validation of AR solutions in the literature is generally conducted through statistical analysis (40%), followed by comparative evaluations, laboratory tests, and field tests. This study emphasizes that while AR has demonstrated numerous benefits in medical practice and education, future development should focus on exploring more integrated multifunctional capabilities, conducting cost-benefit analyses, and expanding implementation to other medical subspecialties such as dermatology or dentistry. With the integration of advanced technologies and broader evaluation approaches, AR has the potential to become an important component of modern medical practice standards.

Despite these promising results, several gaps remain in the current body of literature. There is a limited number of quantitative studies that rigorously assess AR's impact on clinical outcomes, such as surgical accuracy, operating time, or patient recovery metrics. Additionally, existing research tends to concentrate on a few specialized areas, particularly neurosurgery and orthopedics, while other important fields—such as dermatology, rehabilitation, pediatrics, and dentistry—remain underrepresented. Furthermore, few studies have explored the economic feasibility of AR adoption, including cost-efficiency, resource optimization, and its broader financial implications for healthcare systems.

Future research should address these gaps by expanding AR investigations into a wider range of medical subspecialties, incorporating cost–benefit analyses, and evaluating system-level outcomes. Exploring references from additional academic databases and conducting deeper analyses of the strengths and limitations of various AR implementations will be essential to building a more comprehensive and interdisciplinary understanding of AR's role in healthcare innovation. With ongoing technological advancements and more holistic evaluation approaches, AR is poised to become an integral part of modern medical practice. Future work should therefore not only advance AR hardware and algorithms, but also develop explicit interdisciplinary collaboration models and ethical frameworks for AR deployment in healthcare. Co-design approaches that bring together surgeons, nurses, biomedical engineers, HCI researchers, and data scientists could help ensure that AR systems are both technically robust and aligned with real clinical workflows and constraints. At the same time, ethical considerations need to be systematically integrated into AR studies, including clear procedures for patient consent in telementoring scenarios, policies for secure storage and transmission of AR visual data, transparency and accountability in AI-assisted overlays, and strategies to mitigate potential cognitive overload or over-reliance on AR guidance. Addressing these issues will be crucial for translating AR from promising prototypes into safe, trustworthy, and sustainable components of modern surgical education and clinical practice.

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