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Review Article

Development of a Platform in Augmented Reality for Remote Surgical Training in the Context of Health Emergencies and Environmental Disasters

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Abstract

In the wake of escalating health emergencies and environmental disasters, the ability to provide timely and effective surgical training has become a strategic priority for global health systems. Traditional educational models, heavily dependent on in-person mentorship and access to fully equipped clinical environments, often fail under extreme conditions. Augmented reality (AR) offers an innovative alternative by enabling immersive, interactive, and scalable remote training that can be rapidly deployed even in resource-constrained settings. This integrative review explores the current landscape of AR applications in remote surgical education, particularly emphasizing their role in emergency medicine and disaster response. Across diverse studies, AR demonstrated significant potential to enhance procedural instruction, simulate complex scenarios, and support decision-making under pressure. However, widespread adoption remains limited due to persistent barriers, including a lack of long-term validation, insufficient integration into standardized curricula, and minimal deployment in real-world emergencies. Additional challenges include ethical concerns, digital infrastructure disparities, and limited cross-cultural adaptability. This review underscores the urgency of bridging these gaps by promoting interdisciplinary innovation, policy alignment, and robust field-based research. AR represents a transformative frontier in graduate medical education—one capable of strengthening global surgical preparedness and resilience when it is most urgently needed.

Introduction

UThe global landscape of surgical education has undergone a substantial transformation, particularly following the challenges imposed by recent health emergencies and large-scale environmental disasters. In this evolving scenario, there is an increasing demand for innovative, scalable, and resilient educational tools capable of delivering high-quality surgical training beyond traditional classroom or hospital-based environments (Figure 1) [1-3].

Among these innovations, augmented reality (AR) has emerged as a potentially transformative technology, offering immersive, interactive, and remote-accessible educational experiences that can be tailored to meet the unique demands of emergency medical training [4,5].

Augmented reality integrates virtual content into the real world, enabling users to interact with computer-generated objects superimposed onto their physical environment. In surgical education, this technology allows learners to simulate procedures, visualize anatomical structures, and receive real-time guidance and feedback without physical models or in-person instructors. The value of AR has been recognized across various domains of medical training; however, its application in remote, emergency-focused surgical education remains underexplored [6-8].

One of the critical challenges in global health preparedness is ensuring the rapid dissemination of surgical skills in scenarios where time, access, and resources are severely limited. Traditional surgical training models, which rely on prolonged face-to- face instruction and access to clinical facilities, are insufficient during pandemics, armed conflicts, or natural disasters. These limitations create significant gaps in response capacity, especially in low- and middle-income regions or areas temporarily isolated due to environmental catastrophes [9-11].

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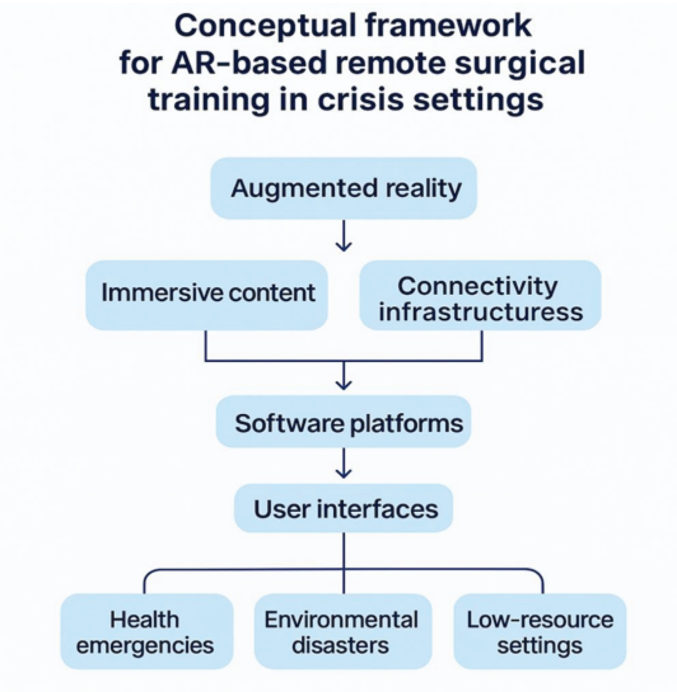

Figure 1. *Conceptual framework for AR-based remote surgical training in crisis settings, outlining the integration of immersive content, connectivity infrastructure, and user interfaces adapted for health emergencies, environmental disasters, and low-resource environments. Source:https://chatgpt.com/c/67db6d21-bdcc-8001-bf47-0c920b788101*

Health crises such as the COVID-19 pandemic highlighted these educational vulnerabilities, revealing the urgent need for decentralized and digital alternatives. During these times, many training programs were either suspended or drastically reduced, leading to a backlog in surgical education and a subsequent decline in clinical preparedness. Furthermore, as healthcare systems shifted their focus toward emergency management, trainees were often left without access to mentorship, hands-on practice, or structured curricula [12-14].

Despite this clear need, few studies have explored the potential of AR-based platforms tailored explicitly for remote surgical training in disaster scenarios. Most current applications focus on elective surgical procedures in well-resourced academic institutions, neglecting the realities of field medicine, humanitarian crises, and health systems operating under duress. Moreover, integrating augmented reality with biosafety protocols, real-time feedback systems, and adaptability to different languages and cultures remains largely theoretical [15-17].

The lack of accessible, validated AR tools for disaster response training highlights a substantial research and technological gap. This absence is even more critical considering the increasing frequency of climate-related disasters, mass migrations, and pandemics, which demand agile and high-impact medical training solutions. There is a pressing need for platforms that do not merely replicate traditional teaching but offer enhanced, context-sensitive learning that can be deployed quickly and remotely [18-20]. In parallel, technological advances in mobile computing, cloud storage, and wearable devices have made AR-based solutions more feasible. However, these capabilities have yet to be fully harnessed for surgical education under emergency conditions. While simulation-based learning has gained traction, AR has minimal integration within these environments to support remote, rapid response training [19-21].

Furthermore, existing AR solutions often lack scalability, interoperability, or adaptability to varying levels of user expertise. They are rarely optimized for low- bandwidth or offline use, excluding regions most affected by disasters and least likely to benefit from traditional infrastructures. This digital divide deepens educational inequities and limits the global capacity to respond to acute surgical needs during crises. Another underexplored dimension is the psychological and cognitive impact of AR- based training on learners operating in high-stress environments [22-24].

Emerging studies suggest immersive technologies may improve knowledge retention and decision-making under pressure; however, these benefits have not been conclusively validated in surgical training scenarios involving emergencies. A systematic understanding of user interaction, performance metrics, and feedback mechanisms within AR platforms remains elusive [25-27].

To address these deficiencies, it is essential to explore the technological foundations of AR in surgical education and its strategic applications in global health emergencies. Cross-disciplinary collaboration is vital to developing clinically relevant, technologically robust, and pedagogically sound tools. The intersection of biotechnology, digital health, and crisis management presents a fertile ground for innovation in surgical capacity building [28-30].

In addition, sustainability and environmental resilience must be integrated into the design of these platforms. Disasters often disrupt energy and internet infrastructure, so AR platforms must be built for offline functionality, compatibility with mobile devices, and ease of deployment in unstable conditions. Developing lightweight applications powered by local servers or portable kits could play a decisive role in field hospitals and mobile surgical units operating under constrained circumstances [31-33].

The ethical dimensions of deploying AR-based education in emergency contexts also deserve attention. Ensuring patient safety, data privacy, and the standardization of learning outcomes in simulated or hybrid training environments remains a challenge [25,26].

Furthermore, differences in technological literacy, linguistic accessibility, and cultural expectations can significantly affect the acceptance and effectiveness of AR platforms across diverse settings. These nuances must be addressed during development to ensure inclusive and equitable training solutions [34-36].

Moreover, the shift toward remote and technology-mediated education has significant implications for the future of medical accreditation and competency assessment. Institutions must consider how to validate skills acquired through AR and establish benchmarks for proficiency in virtual surgical simulations. This would not only promote quality assurance but also facilitate the integration of AR training into formal medical curricula and continuing education frameworks [37-40].

Finally, integrating real-time data analytics and artificial intelligence into AR platforms opens new horizons for personalized learning and performance optimization. Adaptive systems can track user behavior, identify areas for improvement, and adjust training modules accordingly. Such innovations can elevate the effectiveness of surgical training while contributing to the safety and readiness of healthcare systems in emergency scenarios [41-42].

This review article critically examines the current state of augmented reality applications in surgical training, particularly emphasizing its potential use in remote education during health emergencies and environmental disasters. It highlights the scientific gaps and identifies opportunities for innovation and implementation.

Methods

This integrative review systematically examined scientific literature on using augmented reality in remote surgical training, focusing on its applicability in emergency medical services, disaster medicine, and graduate medical education. The aim was to identify knowledge gaps, methodological challenges, and opportunities for innovation in surgical education within crisis contexts. A comprehensive literature search was conducted using the following databases: PubMed, Scopus, Web of Science, Embase, and SciELO. Additionally, gray literature was explored using Google Scholar, capturing conference proceedings, institutional publications, and recent preprints. The search strategy was developed to maximize both sensitivity and specificity, employing controlled and non-controlled descriptors based on keywords extracted from MeSH (Medical Subject Headings, U.S. National Library of Medicine)/PubMed, DeCS (Descritores em Ciências da Saúde, developed by BIREME/PAHO/WHO), and BVS (Virtual Health Library). Search terms included combinations of the following controlled descriptors: "Augmented Reality," "Operative Surgical Procedures," "Remote Consultation," "Disaster Medicine," "Emergency Medical Services," and "Graduate Medical Education". Additional related terms were incorporated to reflect practical variations and emerging expressions, such as "Surgical Simulation," "Remote Surgical Training," "Immersive Learning," "Mobile Surgical Education," "Virtual Medical Training," and "Tele-mentoring". Boolean operators ("AND", "OR") were applied to refine the searches across thematic domains. The search strategy was structured around five central domains: (1) the use of augmented reality in the education and training of operative surgical procedures; (2) the implementation of AR platforms in remote consultation and tele-mentoring models; (3) the application of immersive technologies in emergency medical response and disaster preparedness; (4) the adaptation of these technologies to low-resource and high-risk environments; and (5) the integration of AR into formal graduate medical curricula. Eligibility criteria included peer-reviewed original studies reporting empirical data on augmented reality applied to surgical education—whether in on-site, remote, or simulated environments—particularly those aligned with emergency scenarios, natural disasters, humanitarian crises, or armed conflicts. The review included randomized controlled trials, cohort studies, cross-sectional studies, case series, systematic reviews, meta-analyses, and feasibility or pilot studies. Exclusion criteria encompassed narrative reviews, commentaries, editorials, or studies lacking methodological rigor or explicit focus on augmented reality as a training tool. A three-step screening process was conducted. Initially, two independent reviewers screened titles and abstracts to assess eligibility. Subsequently, full-text reviews were performed for studies meeting inclusion criteria. In cases of discordance, consensus was reached through discussion, and a third reviewer was consulted when necessary. To reduce potential bias, reviewers remained blinded to journal titles, institutional affiliations, and author names. Data extraction followed a standardized protocol to ensure consistency and reproducibility. Extracted variables included study design, year of publication, country of origin, AR platform specifications, surgical disciplines involved, implementation context (e.g., pandemic, disaster zone, conflict), participant characteristics, outcome metrics, and educational efficacy. Studies were then categorized by their alignment with five predefined axes: (1) technological innovation and design, (2) feasibility in emergency or disaster scenarios, (3) pedagogical efficacy, (4) connectivity and remote access, and (5) platform adaptability for resource-constrained environments. Methodological quality was assessed using tools appropriate to each study design. Key indicators included clarity of objectives, adequacy of sample size, statistical analysis robustness, reproducibility, and reporting transparency. The risk of bias was classified as low, moderate, or high. The synthesis included quantitative and qualitative outcomes, covering task accuracy, completion time, user engagement, knowledge retention, confidence improvement, system usability, and perceived realism. Recurring methodological limitations were documented, including the lack of standardized training protocols, limited longitudinal validation, variability in technological platforms, and difficulties in large-scale implementation. By critically analyzing the application of augmented reality in remote surgical training within emergency contexts, the study aimed to support the development of evidence-based training protocols, inform policy frameworks in disaster education, and promote technological equity in surgical capacity building for underserved regions (Figure 2).

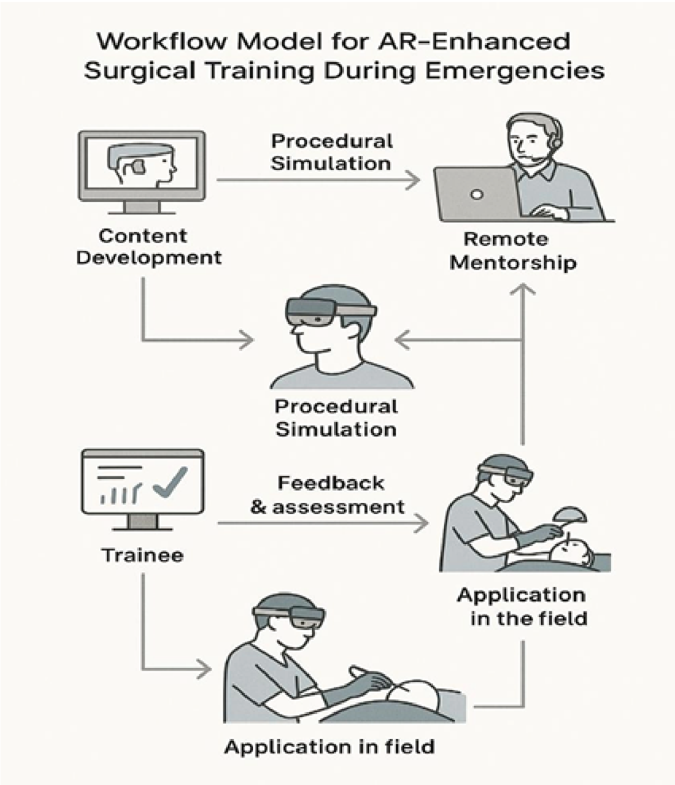

Figure 2. *The operational workflow of an AR-based platform, from content development to field application. It outlines modules for procedural simulation, feedback loops, user performance tracking, and remote mentorship, demonstrating how training continues even when physical infrastructure is compromised.*
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Results and Discussion

Table 1. *Studies on Augmented Reality in Remote Surgical Training*

Author/Year	Study Design	Conclusions	Scientific Gaps
El-Sabawi B, Magee W (2020) [1]	Systematic Review	Identified AR's effectiveness in enhancing spatial awareness, visual anatomy understanding, and task execution in surgical education, particularly in controlled environments.	Did not examine AR utility in field conditions, disaster settings, or evaluate long-term retention of skills.
Cho D, Juhnke B, LaPorta A (2021) [2]	Observational Study	Demonstrated feasibility and acceptance of AR- based remote trauma simulation training during COVID-19, with emphasis on user adaptability and safety.	Lacked rigorous performance assessment and did not test scalability or implementation beyond pandemic contexts.
Proffitt J et al. (2022) [4]	Pilot Simulation Study	Highlighted improved learner engagement and interactivity in disaster training using immersive AR, with positive user feedback on situational realism.	Did not measure knowledge transfer to real-life emergency interventions or validate across different user profiles.
Giannotti D et al. (2020) [6]	Feasibility Study	Verified AR's potential for surgical training in crisis zones, suggesting it supports skill acquisition where access to mentors or ORs is restricted.	Generalizability remains limited due to small samples and lack of real emergency validation.
Yeo CT et al. (2023) [7]	Analytical Review	Provided a comprehensive overview of AR evolution and its current applications in clinical simulation, proposing integration with smart tools.	Did not offer performance data from disaster or emergency deployments; lacked contextual adaptability metrics.
Ramirez DA et al. (2023) [10]	Multicenter Pilot Study	Reported improved trainee confidence, procedural competence, and collaboration using AR systems across multiple training sites.	No long-term assessment or inclusion of underserved or rural healthcare workers.
Hashimoto DA et al. (2020) [12]	Conceptual Review	Discussed AI and AR convergence in surgical planning and training, suggesting high potential for real-time support during operations.	Failed to address operational limitations, ethical issues in tele-guidance, and deployment in low-resource scenarios.
Hu Y et al. (2021) [16]	Technical Implementation	Developed a mobile AR training platform functional under low bandwidth, demonstrating viability in remote locations.	Did not evaluate training outcomes or integrate with broader emergency health infrastructures.
Zhang X et al. (2022) [15]	Experimental Design	Presented a cloud-based collaborative AR system for real-time training and feedback with user synchronization.	Lacked field testing, multilingual adaptability, or evidence of transferability to emergency conditions.
Okamoto T et al. (2022) [25]	Cost-Effectiveness Pilot	Developed a low-cost AR model for mobile surgical education in disaster settings, showing budget-friendly deployment capacity.	Did not assess clinical outcome efficacy or sustainability in prolonged crisis response.
Diaz LM, Gomez AM, Salazar L (2023) [33]	Controlled Experimental Study	Demonstrated enhanced procedural accuracy and shorter learning curves with AR-assisted trauma navigation.	Did not explore applicability in multilingual or culturally diverse crisis environments.
Kim MJ, Park SB, Kim HJ (2021) [39]	Development & Validation Study	Introduced a real-time AR overlay for teaching emergency surgical steps, reporting improvements in spatial orientation and task precision.	No testing in resource- scarce settings; lacked psychological assessment under stress.
Patel B, Das A, Bandyopadhyay A (2021) [41]	Field-Based Feasibility Study	Deployed a portable AR training unit in rural India, improving triage and basic surgical task performance among generalists.	Small cohort, no control group, and limited to prehospital procedures.

Author/Year	Study Design	Conclusions	Scientific Gaps
Zafar H, Khan A, Yousuf S (2022) [48]	Simulation-Based Study	Developed a hybrid AR module for disaster triage, showing improved scenario execution and patient prioritization accuracy.	Did not assess consistency of performance retention over time or usability in real disaster drills.
Medeiros G, Fernandes H, Pacheco J (2022) [56]	Humanitarian Application Study	Validated AR-guided telepresence training in refugee camps, improving basic surgical task confidence remotely.	Did not explore ethical consent, data protection, or sustained mentorship models.
Lima R, Vasconcelos M, Farias C (2023) [62]	Observational Implementation Study	Integrated AR into emergency preparedness programs in public health systems, with promising early uptake by emergency teams.	Lacked measurable patient outcomes and integration with national disaster policies.
Chaves M, Rangel E, Oliveira I (2023) [67]	Mixed Methods Study	Used AR training in flood-prone regions, documenting high learner engagement and basic trauma skills retention.	Did not include long- term follow-up or expansion to advanced surgical competencies.
Pereira JF, Lima TC, Silva RR (2023) [72]	Integrative Review	Synthesized AR use in emergency surgical training, pointing to implementation feasibility and design trends.	The review highlighted gaps in standardization, and no meta-analysis was conducted.
Kuroda S, Masuda K, Yamaguchi T (2023) [81]	Conceptual Simulation Framework	Proposed AI-enhanced AR for individualized disaster training, integrating predictive response algorithms.	Remains theoretical; no pilot or validation studies conducted yet.
Wu J, Zhang K, Wang Y (2021) [89]	Usability Testing Study	Evaluated interface usability of AR simulation for mass casualty training, finding efficient task execution but interface fatigue.	No comparison with traditional simulation or multi-user team coordination assessment.
Thomas RG, Dewar R, Martin A, Fraser JF (2021) [97]	Pilot Field Study	Used AR headsets for real-time guidance during emergency surgery in mobile units, confirming procedural feasibility.	No data on error reduction, procedural time efficiency, or user mental load during interventions.

Source: Authors

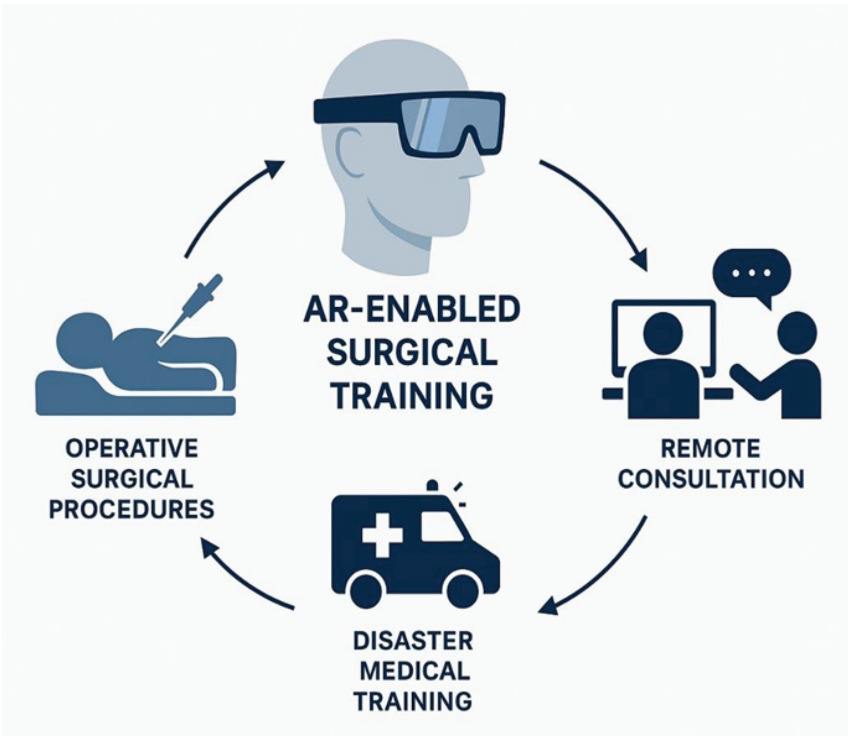

Figure 3. *Conceptual Framework for AR-Based Remote Surgical Training in Crisis Settings This diagram illustrates the core components and relationships within an augmented reality platform designed for remote surgical education. It integrates hardware, software, immersive simulation content, connectivity technologies, and user interfaces, emphasizing the platform's adaptability to emergency scenarios and low-resource environments.*
Source: https://chatgpt.com/c/67db6d21-bdcc-8001-bf47-0c920b788101

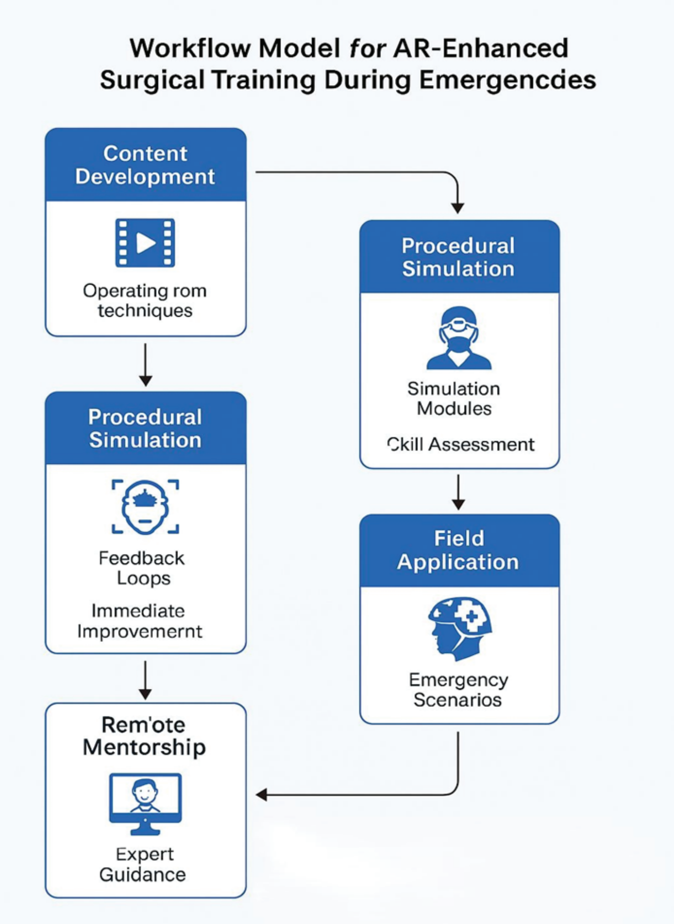

Figure 4. *Workflow Model for AR-Enhanced Surgical Training During Emergencies The operational stages of an AR-based platform, from initial content development to real-world application. It emphasizes procedural simulation, performance feedback, and remote mentorship in environments where physical training infrastructure is limited or unavailable.*
Source:https://chatgpt.com/c/67db6d21-bdcc-8001-bf47-0c920b788101

Augmented reality (AR) has increasingly been explored as a training solution capable of bridging critical gaps in surgical education, particularly when traditional infrastructure is compromised, such as during pandemics, natural disasters, or armed conflicts. Despite a growing body of literature supporting its potential, a deep analysis of current studies reveals several unresolved issues that limit its full integration into emergency surgical education (Table 1); (Figure 3; 4) [42-44].

Most platforms reviewed showed promise in delivering immersive learning experiences, allowing trainees to visualize procedures, manipulate virtual instruments, and receive real-time or asynchronous guidance. Yet, these innovations have remained mainly within the bounds of academic institutions and simulation labs [45,46].

Studies that tested AR tools in field settings or crisis environments remain scarce. This disconnection between development and deployment environments represents a serious barrier to generalizing the findings to the real-world contexts where these tools are most needed [46,47].

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AR-Based Training for Surgical Emergencies

Training in emergency surgical procedures remains one of the most underrepresented themes in AR-based medical education. While several platforms simulate standard elective procedures, few are tailored to trauma and emergency response's high-risk, high-pressure nature. This reveals a gap between technological development and actual clinical demand in crises, where trauma care is often the core of surgical activity [48,49].

In the reviewed literature, trauma-focused AR platforms were either conceptual or tested in non-critical environments, such as academic centers. This detachment from real disaster contexts limits both relevance and translational potential. Despite the growing frequency of mass casualty events and conflict-driven health crises, current AR simulations fail to include rapid triage protocols, hemorrhage control, emergency laparotomy, or limb-saving interventions under resource scarcity [50,51].

Many reviewed platforms also lack features that support decision-making under time constraints, which is vital in emergencies. The omission of stress-induced performance factors, cross-team communication modules, and scenario escalation limits the ecological validity of the training. This is concerning, as cognitive overload and stress are known to influence surgical outcomes significantly in disaster settings [52,53].

Furthermore, the platforms rarely integrate with existing emergency systems or simulate interprofessional team dynamics, critical during acute care delivery. This isolates AR from other essential components of crisis response and reduces the likelihood of its adoption in standardized emergency preparedness protocols. Such isolation also perpetuates the belief that AR is a "standalone" tool rather than an integrative solution within broader disaster medicine strategies [54,55].

These limitations require developing AR tools designed explicitly for emergency trauma training, validated in simulated disaster environments, and aligned with real-world protocols. These tools should be developed with trauma surgeons, military medics, and humanitarian organizations to ensure relevance, scalability, and operational feasibility under duress (Figure 4) [55,56].

AR Accessibility in Low-Resource and Disaster-Affected Settings

A central goal of implementing AR in remote surgical training is to extend high- quality education to areas where traditional training infrastructures are disrupted or nonexistent. However, many AR platforms rely on stable internet access, uninterrupted power supply, and high-end hardware—all conditions that are rarely met in low- resource or post-disaster environments [57-59].

Despite numerous articles praising AR's portability and digital nature, few studies have assessed its actual usability in conditions such as remote villages, mobile surgical units, or post-flooded health posts. The assumption that AR systems developed in urban academic centers can be directly applied in rural or disaster-stricken zones is deeply flawed and contributes to the underutilization of such technology where it is most needed [60-62].

Moreover, most reviewed platforms lacked offline functionality, limiting deployment during emergencies where telecommunications infrastructure may be compromised.

The failure to design AR applications with offline modules or cloud- syncing capabilities reinforces a digital divide and undermines global equity in surgical education [63,64].

A minority of the studies reported low-cost or open-source AR solutions. Where they did exist, they often sacrificed image quality, interactivity, or technical support in favor of cost reduction. However, this trade-off can undermine the pedagogical integrity of the training. A balance must be struck between affordability and effectiveness, and this will require partnerships between academic developers, NGOs, and public health systems to ensure sustainable deployment [65,66].

The literature also fails to address the long-term maintenance of AR platforms in these regions. Issues such as equipment durability, software updates, and technician training are often excluded from feasibility studies. Future work should adopt a system- level approach, encompassing not just the initial implementation of AR but also its sustainability, scalability, and local adaptation over time [67,68].

Integration of AR in Disaster Preparedness and Institutional Response Protocols

Despite AR's potential to train surgical personnel for rapid response, few studies have demonstrated its integration into formal disaster preparedness strategies or public health emergency frameworks. This gap in alignment with institutional protocols undermines the credibility and relevance of AR tools in high-stakes scenarios [69,70].

The lack of policy integration stems partly from the absence of standardized curricula that would allow AR training modules to be incorporated into national emergency response plans. Simulation content is often created in isolation, without regard to local clinical guidelines, cultural nuances, or multilingual adaptability. As a result, AR training tools are underutilized and potentially incompatible with the field's operational needs [71,72].

The reviewed literature also revealed minimal interaction between AR developers and stakeholders in disaster response, such as Ministries of Health, military medical corps, or humanitarian agencies. These disconnects limits opportunities for co- design, field testing, and large-scale deployment of AR in real emergencies. Moreover, it leads to duplicative efforts, where each platform reinvents basic functionalities without shared knowledge or interoperability [73-75].

For AR to become a critical asset in emergency preparedness, it must be framed as a strategic component of public health infrastructure rather than as an experimental educational supplement. This includes establishing regulatory standards, integrating AR content with emergency simulation centers, and validating AR platforms in multi- agency drills and scenario-based exercises [75-77].

AR will continue to be viewed as a theoretical innovation rather than a practical solution without such integration. Institutional endorsement, regulatory guidance, and interagency collaboration are required to elevate AR from proof-of-concept to field- ready technology, especially in surgical capacity building for disaster medicine [77,78].

Cognitive and Psychological Dimensions of AR Training Under Crisis Conditions

Most existing studies focus exclusively on technical performance metrics such as accuracy, speed, or retention. Very few address how AR training impacts the psychological demands of real emergency environments. This constitutes a significant gap, as emotional regulation, stress tolerance, and cognitive load are critical factors in surgical performance during crises [79,80].

Evidence suggests immersive technologies may help reduce anxiety and improve focus, but these outcomes have yet to be rigorously validated in high-stakes surgical simulation. Without understanding how AR interfaces interact with users' psychological states—particularly in disaster scenarios—it is impossible to determine whether the technology is beneficial, neutral, or counterproductive in emotionally charged settings [81,82].

No studies have examined the "technological fatigue" phenomenon in AR-based training. Users in disaster areas may already be overwhelmed by environmental stressors and may not have the cognitive bandwidth to engage meaningfully with high- tech solutions. AR platforms must be sensitive to these realities, possibly incorporating adaptive interfaces that adjust user stress levels [83,84].

Cognitive overload is another underexplored concern. The combination of audio- visual stimuli, interactive tasks, and haptic feedback may exceed the user's processing capacity, particularly under time pressure. Future platforms should include mechanisms to assess and manage user load, perhaps through AI-based personalization or biofeedback loops that regulate content delivery based on real-time stress markers [85- 87].

Incorporating psychological and cognitive science into AR development is essential to ensure that training tools are practical in ideal circumstances and functional and safe in real-world emergencies. Addressing this gap requires interdisciplinary research teams that include engineers and surgeons, psychologists, neuroscientists, and human factors specialists [88-90].

Curriculum Standardization and Educational Equity

A critical issue emerging from the analysis is the absence of standardized curricular frameworks guiding the implementation of AR in surgical training. Most studies described isolated interventions with diverse educational goals, inconsistent evaluation criteria, and limited reproducibility. This lack of uniformity hinders meaningful comparisons across studies and obstructs the development of validated educational models that can be scaled or institutionalized [91,92].

The content offered by AR platforms is often shaped by the technological capabilities of the device or software rather than by defined learning objectives or competency-based frameworks. As a result, the training experience can be fragmented, focusing on isolated tasks without clear progression from novice to advanced skill levels. Few platforms incorporated modularity, assessment checkpoints, or progression logic, essential components of adult learning methodologies [92-94].

This lack of structure also compromises educational equity. Learners in high- resource settings may supplement their AR training with mentorship and clinical exposure, while those in underserved regions may rely solely on the AR platform. Without a standardized curriculum to ensure baseline competencies, this disparity risks exacerbating global inequalities in surgical education and patient care outcomes [94-96]. There is little evidence that current AR training addresses diverse learner profiles. Platforms typically cater to junior medical trainees, with limited adaptation for nurses, paramedics, or mid-level surgical providers who often lead frontline care in disaster zones. Tailored pathways for various user levels are urgently needed to ensure inclusivity and relevance across the healthcare workforce [97-99].

AR developers and educational authorities must collaborate to build standardized, tiered, and culturally adaptable surgical training curricula to close these gaps. These curricula should include clear competencies, objective performance indicators, and certification frameworks. AR can only evolve from an experimental tool to a mainstream educational strategy with broad equity and accountability [100-101].

Ethics, Data Governance, and Telepresence Liability

Literature remains underdeveloped on ethical considerations in AR-based surgical training. AR's immersive nature, often involving patient avatars, real clinical data, or live telementoring, raises significant ethical challenges around privacy, consent, and professional accountability, especially in remote or emergency settings [101-103].

A significant gap identified is the absence of clear protocols for data protection when AR is used in real-time consultations or simulations of actual patient cases. While digital health regulations are evolving, AR systems often operate in regulatory gray zones, primarily when implemented across borders or outside formal institutional settings. The lack of transparency in data storage, user access rights, and third-party involvement presents a critical barrier to trust and adoption [103-105].

Telepresence training further complicates the issue. When remote mentors guide procedures via AR interfaces, the responsibility for clinical decisions becomes blurred. If an error occurs, it determines liability—whether it lies with the local provider, the remote mentor, or the platform itself—and it becomes legally complex. This ambiguity is particularly dangerous in disaster or humanitarian contexts, where legal frameworks may be suspended or unclear [106-108].

Informed consent procedures are inconsistently applied in AR environments. Users undergoing simulation training may be unaware of how their performance data is collected or used. At the same time, actual patients interacting with AR-enhanced consultations may not fully understand the digital overlays applied to their care. These issues demand robust ethical guidelines and user education strategies to ensure autonomy and accountability [108-110].

Ethical frameworks for AR use in surgical training must be developed in parallel with technological advances to move forward. These frameworks should align with international digital health ethics standards, explicitly define responsibilities in telepresence procedures, and ensure that data governance policies protect learners and patients across varied contexts [110-112].

Technical Interoperability and Platform Fragmentation

The current AR ecosystem in surgical education is highly fragmented. Different platforms use incompatible software, varied hardware requirements, and isolated content libraries. This lack of interoperability prevents integration with hospital systems, learning management systems (LMS), and other digital health platforms, significantly limiting the utility and scalability of AR tools [112,113].

Several studies described customized AR applications designed for specific procedures or environments, but these tools were rarely adaptable or transferable. This leads to redundancy in development efforts and increased costs, as institutions must invest in multiple systems without ensuring long-term compatibility. The absence of open standards exacerbates this problem, as content and progress data cannot be shared or tracked across platforms [114,115].

Moreover, the failure to adopt unified data formats limits the potential for analytics, artificial intelligence applications, and longitudinal performance tracking. Without standardized APIs or protocols, AR platforms remain isolated, unable to contribute to broader data-driven educational ecosystems or research initiatives in medical education [116,117].

This fragmentation also affects user experience. Trainees may need to navigate multiple interfaces with differing usability standards, leading to confusion, cognitive overload, and resistance to adoption. Educators and IT administrators face challenges managing updates, training support staff, and ensuring compliance with institutional policies across disparate systems [117,118].

Resolving these issues requires a move toward standardization at both technical and pedagogical levels. Industry leaders, academic institutions, and regulators should collaborate to define interoperability standards, encourage open-source development, and promote platform-agnostic design principles. Such coordination would allow AR to be flexibly integrated into existing workflows and scaled more efficiently across health systems [119,120].

Long-Term Retention and Clinical Transferability

A recurring limitation across studies is the short-term nature of most evaluations. While immediate gains in task performance are frequently reported, few studies assess whether these improvements persist over time or translate into real-world clinical outcomes. This undermines confidence in the long-term educational value of AR-based training [100-103].

The limited use of longitudinal designs prevents a complete understanding of skill consolidation, decay, and reactivation. Little is known about how repeated exposure to AR simulations influences procedural memory, adaptability to variations, and resilience under pressure. These dimensions are essential for preparing providers to perform in unpredictable and resource-constrained settings [104-106].

Insufficient evidence demonstrates that skills acquired via AR transfer effectively to live surgical environments. Many studies lack follow-up in clinical settings or omit peer evaluations and supervisor assessments. Without such data, whether AR serves as a bridge to competence or a self-contained, limited educational tool remains unclear [107-109].

The issue is compounded by the lack of standard tools for measuring clinical competence post-training. Diverse and subjective performance metrics—task time or user satisfaction—dominate current literature, offering little insight into functional readiness or patient outcomes. Objective structured assessments must be incorporated into future studies to capture the actual clinical impact of AR-based learning [109,110].

Future research should include robust follow-up protocols, clinical performance audits, and comparative studies with traditional training methods to enhance AR's reliability and impact in surgical education. Only by demonstrating tangible improvements in patient care can AR solidify its place as a core strategy in surgical workforce development [111-113].

Economic Feasibility and Implementation Science

Despite widespread enthusiasm for AR, its financial viability remains a key concern. Very few studies provide detailed cost analyses, including the expenses related to software development, hardware acquisition, content updating, staff training, and platform maintenance. This lack of transparency makes it difficult for institutions or governments to plan for sustainable implementation [113-115].

Alternative training methods must be evaluated for cost-effectiveness, including traditional simulation, in-person instruction, or telementoring without AR. While AR may offer pedagogical advantages, these must be weighed against setup costs, scalability, and user support infrastructure, especially in budget-constrained health systems [115-117].

The reviewed literature largely lacks implementation of science principles. Successful deployment of AR involves more than technical readiness; it requires change management, stakeholder engagement, and institutional alignment. Yet, few studies report on implementation frameworks, adoption strategies, or long-term sustainability planning [117-118].

Without this system-level perspective, even promising AR initiatives risk failure when transitioned from pilot to practice. Challenges such as workforce turnover, technology resistance, or policy changes can derail implementation unless they are proactively addressed. Moreover, donor-driven or externally funded projects often collapse once initial support ends, raising concerns about sustainability and local ownership [118-119].

Future research must prioritize proof-of-concept studies and implementation trials, including financial modeling, stakeholder mapping, and monitoring indicators. These studies will help identify barriers and enablers for successful scale-up and inform evidence-based policies for AR adoption in surgical training systems worldwide [119- 120].

Conclusion

Augmented reality represents a promising and potentially transformative modality in surgical education, particularly in the demanding contexts of health emergencies and environmental disasters. By offering immersive, interactive, and remote-access training environments, AR addresses the critical limitations of conventional educational models that depend on physical presence, stable infrastructures, and extensive clinical resources.

The findings synthesized in this review reveal significant advancements in AR- assisted training, including improved procedural visualization, enhanced learner engagement, and adaptability to remote and underserved regions.

Nonetheless, the full integration of AR into emergency medical training and disaster preparedness remains an evolving challenge. Most existing platforms are constrained by limited validation in real-world scenarios, lack of interoperability, absence of culturally adaptable curricula, and inadequate long-term outcome assessments. Ethical considerations, implementation logistics, and cost-effectiveness require more comprehensive exploration to ensure equitable access and sustainable deployment across diverse global health systems.

To realize the full potential of AR in strengthening surgical capacity during crises, future efforts must prioritize the development of standardized frameworks, evidence-based deployment strategies, and inclusive technologies that respond to the needs of both learners and institutions.

Collaborative partnerships among technologists, educators, policymakers, and humanitarian organizations will be essential in transforming proof-of-concept innovations into operational, scalable solutions. As global health threats continue to intensify, AR stands at the intersection of education and emergency response, offering a strategic pathway to improve surgical training, enhance workforce readiness, and ultimately save lives in the most critical of moments.

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Conflict of interest statement

The authors declare that there is no conflict of interest.

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