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Review Article

Evaluation of Mixed-Reality Technologies for Anesthesia Education

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ABSTRACT

Mixed-reality technologies, spanning fully immersive virtual reality through augmented and true mixed reality, have moved from novelty devices to a genuinely evaluated component of anesthesia education over the past several years.

This review synthesizes the current evidence for these technologies across the principal domains in which they have been studied: ultrasound-guided regional anesthesia, airway management and cardiac ultrasound anatomy training, and crisis resource management in virtual environments.

Randomized and construct-validation studies indicate that immersive training can produce measurable procedural skill gains for spatially demanding tasks such as needle-guided regional blocks and airway anatomy visualization, generally performing on par with or better than conventional simulation-based teaching on proxy outcome measures.

Evidence for virtual-reality-based crisis resource management training is more preliminary, and trainee and program-level perception data highlight persistent barriers around hardware cost, comfort, and curricular integration.

We conclude that mixed-reality tools are best positioned as a complement that extends training capacity and repeatability rather than a replacement for mannequin-based simulation and bedside supervision, and we identify the modest sample sizes and reliance on proxy outcomes that currently limit stronger claims.

Keywords: *virtual reality; augmented reality; anesthesia education; regional anesthesia simulation; medical simulation training*

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INTRODUCTION

Anesthesiology training has always leaned heavily on simulation, if only because the cost of learning certain lessons on a live patient is unacceptable. Mannequin-based crisis scenarios and part-task

ultrasound trainers have been the workhorses of that effort for two decades, but both have real limits: mannequins are expensive to maintain and schedule, and part-task trainers reproduce a single skill in isolation from the clinical context around it. Mixed-reality technologies - a spectrum running from fully immersive virtual reality (VR), through augmented reality (AR) that overlays digital content on the real environment, to genuinely interactive "mixed reality" (MR) where virtual objects respond to and are occluded by real ones - have moved from novelty to a plausible complement to that existing toolkit [1]. Commodity head-mounted displays, better hand tracking, and falling hardware costs have made it feasible for a residency program to own a small fleet of headsets rather than a single expensive simulation-center rig, and the literature evaluating what these devices actually add to anesthesia education has grown quickly over the past few years [2][3][4].

This review looks at where mixed-reality training has been formally evaluated in anesthesia education: procedural skills such as ultrasound-guided regional anesthesia and airway management, non-technical skills such as crisis resource management, and the broader question of how trainees and programs perceive these tools once they are actually deployed. It is not a claim that headsets are about to replace mannequins or bedside teaching - the evidence does not support that - but a look at where the technology earns its place and where the enthusiasm has outrun the data.

WHAT DISTINGUISHES VIRTUAL, AUGMENTED, AND MIXED REALITY IN THIS CONTEXT

The terms get used loosely enough in the anesthesia literature that a brief clarification is worth making before reviewing outcomes. Virtual reality fully occludes the trainee's view of the physical world and substitutes a rendered environment, typically delivered through a head-mounted display with integrated tracking; the trainee's hands may be represented by controllers or by markerless hand tracking, and the surrounding operating room, patient, and equipment are entirely simulated. Augmented reality instead keeps the physical world visible and adds a digital layer on top of it - a virtual needle trajectory projected onto a real ultrasound phantom, for instance, or vital-sign trends superimposed on the trainee's field of view during a procedure. Mixed reality is sometimes used as a synonym for AR and sometimes reserved for systems in which virtual objects interact convincingly with real ones, including occlusion (a real hand passing in front of a virtual structure blocks it appropriately) [5][6].

This distinction matters clinically because the two approaches solve different problems. VR is well suited to scenarios where the entire clinical environment needs to be simulated, such as a crisis event in an operating room, because nothing about the real world needs to be preserved in the trainee's view. AR and true MR are better suited to procedural skills that are anchored to a real physical target - a phantom, a mannequin arm, or eventually a real patient - because the trainee still needs tactile and visual feedback from that real object while gaining an overlay of information they cannot normally see, such as needle-tip depth or nerve location relative to surrounding vasculature [7].

PROCEDURAL SKILLS: ULTRASOUND-GUIDED REGIONAL ANESTHESIA

Regional anesthesia has probably received more mixed-reality development effort than any other procedural domain in anesthesiology, and for an intuitive reason: the core cognitive challenge of ultrasound-guided nerve blockade is mentally reconstructing a three-dimensional needle trajectory from a two-dimensional ultrasound image, and that is precisely the kind of spatial problem head-mounted displays are good at externalizing. Early virtual reality regional anesthesia simulators date back to work on axillary block trainers that combined a physical mannequin arm with simulated ultrasound and haptic needle feedback, allowing trainees to practice needle advancement and redirection without a patient at risk [8]. That line of work matured into simulators validated against expert performance benchmarks, with the British Journal of Anaesthesia publishing a virtual reality-based regional anesthesia trainer that demonstrated construct validity - novices and experts performed measurably differently on the simulated task in ways that tracked real clinical skill [9]. Commentators surveying the broader field have framed immersive VR platforms as plausibly "the next frontier" in anesthesiology simulation training precisely because of this early success in regional anesthesia, even as they caution that the label has been applied to technologies at very different stages of validation [10].

More recent work has moved from simple construct validation toward randomized comparisons of VR training against conventional teaching. A randomized controlled trial evaluating VR-taught ultrasound-guided needling skills found that trainees who trained in the virtual environment acquired hand-eye coordination and needle-tracking skills that transferred to a subsequent assessment, suggesting the skill is not simply an artifact of the simulated environment but generalizes at least to a bench model [11]. A separate design-and-validation study of a purpose-built VR trainer for ultrasound-guided regional anesthesia reported that the simulator distinguished between experience levels and that trainees rated the experience favorably for realism and usefulness, reinforcing that the underlying construct validity finding from a decade earlier still holds with newer hardware [12].

Augmented reality has taken a complementary route,

overlaying the planned or actual needle trajectory directly onto the operator's view of a phantom or model rather than replacing the ultrasound image with a virtual one. An exploratory study of augmented reality applied to ultrasound-guided regional anesthesia models reported that trainees found the superimposed guidance intuitive for understanding needle-to-target relationships, and that the technology has plausible near-term application in supervised training before its use is considered on real patients [7]. A recent systematic review pooling this literature concluded that extended-reality training modalities for ultrasound-guided regional anesthesia produce skill gains comparable to, and in some outcome measures better than, traditional simulation-based teaching, though the review also flagged substantial heterogeneity in outcome measures across the included trials, which makes head-to-head comparison across studies difficult [13]. A parallel opinion piece in Current Opinion in Anaesthesiology framed emerging technologies including extended reality as a route to expanding regional anesthesia training capacity beyond the limited number of supervised cases a given trainee can accumulate during residency, particularly relevant in settings where regional anesthesia expertise is not evenly distributed geographically [14]. A related application described in the cardiothoracic anesthesia literature used augmented-reality overlay for rescue transesophageal and point-of-care ultrasound acquisition during residency training, extending the same logic - guidance overlaid on a real probe and a real patient - beyond peripheral nerve blocks into broader point-of-care ultrasound education [15].

PROCEDURAL SKILLS BEYOND REGIONAL ANESTHESIA: AIRWAY MANAGEMENT AND ECHOCARDIOGRAPHY

Airway management training has also picked up immersive-reality methods, though the emphasis there has tended to be anatomical rather than purely procedural. A randomized controlled trial of immersive virtual reality-assisted anatomy training in a cohort of non-anesthesiology residents found that trainees who studied airway anatomy in an immersive three-dimensional environment before attempting endotracheal intubation on a simulation mannequin performed better on subsequent intubation attempts than those who studied conventional two-dimensional materials [16]. The mechanism proposed is straightforward: airway anatomy is inherently three-dimensional and the spatial relationships between the tongue, epiglottis, vocal cords, and surrounding structures are easier to internalize when a trainee can rotate and inspect a volumetric model than when they are working from static illustrations, even good ones.

Transesophageal echocardiography, a skill that similarly depends on mentally reconstructing three-dimensional cardiac anatomy from a moving two-dimensional image plane, has seen a comparable low-cost VR pilot. A pilot study evaluating a low-cost virtual reality TEE simulator in anesthesiology residents reported feasibility and acceptable trainee-rated realism, with the authors framing the low hardware cost as the more clinically relevant finding than any incremental skill gain, since it addresses one of the recurring objections to simulation-based echocardiography training - namely that commercial TEE simulators are expensive enough that most residency programs cannot afford more than one [17].

NON-TECHNICAL SKILLS: CRISIS RESOURCE MANAGEMENT IN VIRTUAL ENVIRONMENTS

Anesthesia crisis resource management (ACRM) has a long simulation pedigree independent of mixed reality, going back to full-scale mannequin-based operating-room crisis drills designed explicitly to train the non-technical skills - communication, task delegation, situational awareness - that determine outcomes in a genuine intraoperative emergency as much as procedural competence does [18]. The appeal of porting ACRM training into virtual reality is largely logistical: a full-scale mannequin drill requires assembling a multidisciplinary team, a simulation suite, and confederate actors, all at a specific scheduled time, whereas a VR crisis scenario can in principle be run by a single trainee with a headset on their own schedule, repeated as many times as needed, and standardized precisely across every learner.

A serious-game approach to anesthesia-based crisis resource management training, described in the Computers in Entertainment literature, built a game-like virtual environment specifically to train the cognitive and communication skills of ACRM outside the constraints of a physical simulation center, reporting that trainees engaged with the scenario branching logic in ways that mirrored the decision points emphasized in traditional ACRM curricula [19]. A more recent application of the same logic used virtual reality to build a code-trauma crisis resource management training module, again motivated by the practical difficulty of assembling full interprofessional trauma teams for repeated live drills, and reported that the VR module supported the intended learning objectives around role clarity and closed-loop communication during a simulated crisis [20]. Whether skills rehearsed with a single trainee in a headset - without the actual physical presence and behavior of teammates - transfer as effectively to live team performance as full mannequin-based team drills do remains an open and, frankly, somewhat awkward question for a training modality whose target skill set is fundamentally about interpersonal coordination.

PROGRAM-LEVEL EVIDENCE AND TRAINEE PERCEPTIONS

Beyond isolated skill studies, a small number of programs have evaluated mixed-reality curricula as an integrated part of residency training rather than as a one-off intervention. A randomized controlled study with longitudinal follow-up examined virtual reality integrated with a multilevel, team-based pedagogical structure in standardized anesthesiology residency training and reported sustained benefits on the trainees' measured competencies at follow-up rather than only immediately after the intervention, which is a meaningfully stronger claim than the single-session pre/post designs that dominate most of this literature [21]. A separate single-center randomized trial of VR training for anesthesiologists specifically in invasive procedures similarly reported measurable procedural benefit attributable to the VR arm [22].

Adoption, however, depends as much on how trainees and faculty perceive the technology as on what a randomized trial demonstrates about skill transfer, and the perception data are more mixed than the efficacy data. A survey of perceptions and attitudes toward extended-reality applications in medical education from a single anesthesiology residency program found generally favorable attitudes toward the educational potential of the technology, but also practical concerns around hardware comfort, cost, and integration into an already dense residency curriculum that no one currently has much slack to accommodate [23]. A broader narrative review of current clinical and educational uses of immersive reality in anesthesia reached a similar conclusion: the evidence base supports genuine educational value for specific, well-defined skills, but the case for wholesale replacement of existing simulation infrastructure is not yet made, and most programs describing successful implementations are using mixed reality to supplement rather than substitute for mannequin-based and bedside training [2][3]. Simulation centers building hybrid programs, such as the augmented-reality mixed-simulation initiative described by the University of Florida's simulation center, have generally taken this supplementary framing explicitly, layering AR overlays onto existing high-fidelity mannequin platforms rather than treating either technology as a standalone solution [24].

LIMITATIONS OF THE CURRENT EVIDENCE BASE

A few recurring limitations are worth naming plainly rather than glossing over. First, sample sizes in most of the randomized trials reviewed here are modest, generally in the range of a few dozen trainees per arm, which limits confidence in effect-size estimates and makes meta-analytic pooling across heterogeneous outcome measures difficult, as the recent systematic review of extended-reality regional anesthesia training explicitly noted [13]. Second, most outcome measures are proxies - checklist scores, simulated task completion time, self-reported confidence - rather than downstream patient-relevant outcomes such as block success rate or complication rate in real patients trained via mixed reality versus conventional methods; that translational gap has simply not been bridged yet for any of the applications reviewed here. Third, cost and hardware-comfort barriers, repeatedly flagged in the perception literature, are not incidental complaints but real implementation constraints that will determine whether promising efficacy findings ever reach routine use at the program level [23]. Finally, publication in this space skews toward feasibility and pilot-stage reports; the field would benefit from more multi-center trials with pre-registered, clinically anchored endpoints before mixed-reality training can be recommended as a standard rather than an interesting adjunct.

CONCLUSION

Mixed-reality technologies have moved past the proof-of-concept stage for a defined set of anesthesia training applications, most convincingly for ultrasound-guided regional anesthesia and for airway anatomy education, where the underlying skill is fundamentally spatial and the hardware's strengths line up well with the pedagogical problem. Evidence for crisis resource management training in virtual environments is more preliminary and faces a real question about whether interpersonal team skills can be adequately rehearsed without real teammates present. Across every domain reviewed, mixed reality performs best as a complement to established simulation methods rather than a replacement for them, extending training capacity and repeatability rather than displacing mannequins, bedside supervision, or live team drills. Programs considering adoption should weigh the genuine skill-transfer evidence that exists for specific procedural applications against the practical costs of hardware, curricular integration time, and the still-thin evidence connecting simulated performance gains to real patient outcomes.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this work.

Author Contributions

FA conceived the review and drafted the manuscript. EA performed the literature search and contributed to

writing and critical revision of the manuscript. LB contributed to manuscript drafting, critically reviewed the content for intellectual accuracy, and approved the final version. All authors read and approved the final manuscript.

Ethics Statement

This is a literature review; no new human or animal data were collected, and no ethical approval was required.

Data Availability

No new data were generated for this review. All references are publicly available through the cited sources.

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