

# Advances in Simulation and Surgical Skill Training Evolution: Narrative Integrative Review

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## Abstract

*Simulation-based education has emerged as a cornerstone of contemporary general surgery training, driven by increasing emphasis on patient safety, competency-based education, and rapid technological innovation. Traditional apprenticeship models, while foundational, are constrained by reduced operative exposure, work-hour limitations, and variability in clinical case mix. In this context, simulation provides a structured, reproducible, and safe environment for acquisition, assessment, and refinement of surgical skills across the training continuum. This narrative review synthesizes current evidence on the evolution of simulation in general surgery, encompassing educational theory, technological modalities, clinical integration, challenges, and future directions. Low-fidelity task trainers and box simulators continue to play a vital role in foundational skill development, while virtual reality and augmented reality platforms enable immersive, metrics-driven training for minimally invasive procedures. Robotic surgery simulation has become increasingly relevant, supporting credentialing and shortening learning curves before live operative practice. High-fidelity team-based simulation further addresses non-technical skills, including communication, leadership, and crisis management, which are critical determinants of operating room safety. This review also highlights the growing role of tele-simulation and remote mentoring, particularly in low- and middle-income countries, where access to advanced training resources is limited. Persistent challenges include financial constraints, infrastructure requirements, faculty development, variability in validation standards, and limited long-term patient-level outcome data. Future directions point toward artificial intelligence-enabled adaptive learning, extended reality-based virtual operating rooms, integration of simulation analytics with real-world clinical outcomes, and expanded global access through tele-simulation. Overall, simulation-based education is transitioning from a supplementary tool to an integrated educational ecosystem, positioning it as a critical driver of surgical competence, patient safety, and equity in general surgery training.*

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## INTRODUCTION

Surgical training has traditionally relied on the apprenticeship-based “see one, do one, teach one” paradigm, formalized during the Halstedian era [1]. While this model laid the foundation for modern surgical education, it is increasingly constrained by

reduced operative exposure, heightened patient safety expectations, work-hour restrictions, and rapid technological advancement [2–5]. In this evolving landscape, simulation-based education has emerged as a critical adjunct, enabling deliberate, structured, and safe skill acquisition outside the operating room [6–10].

Simulation in general surgery now encompasses a broad spectrum of modalities ranging from low-fidelity task trainers to immersive virtual reality (VR), augmented reality (AR), robotic simulation, and tele-simulation platforms. These tools allow objective assessment, repetitive practice, and competency-based progression, aligning surgical education with contemporary educational theory and regulatory expectations [2, 11].

Simulation allows deliberate, structured acquisition of technical and non-technical skills in a controlled environment, independent of clinical case availability. Importantly, its value lies not only in risk mitigation but also in standardization, objective assessment, and alignment with competency-based medical education (CBME). In general surgery – a discipline characterized by procedural breadth and high-stakes decision-making – simulation has become integral to modern training paradigms [12].

## **EVOLUTION OF SURGICAL TRAINING: FROM APPRENTICESHIP TO COMPETENCY**

The traditional apprenticeship model emphasized experiential learning through graded responsibility but offered limited standardization or objective assessment [1]. Variability in case exposure and trainer expertise often resulted in inconsistent skill acquisition [4]. Over the past two decades, surgical education has shifted toward competency-based medical education (CBME), which prioritizes outcomes, measurable skills, and learner-specific progression rather than time-based training [2].

Simulation plays a central role in this transition by providing reproducible environments in which competencies can be taught, assessed, and remediated before patient contact [3]. In general surgery, this shift has been reinforced by evidence demonstrating that simulation-trained residents achieve higher technical proficiency and transfer skills more effectively to the operating room [6, 13].

### **Educational Theory Underpinning Simulation-Based Training**

Simulation-based surgical education is grounded in established learning theories, particularly deliberate practice and mastery learning [3, 10]. Deliberate practice emphasizes focused, repetitive performance with immediate feedback, while mastery learning requires learners to meet predefined performance benchmarks before progression [3].

Randomized trials and longitudinal studies in general surgery have shown that mastery-based simulation training results in superior skill retention, reduced intraoperative errors, and improved patient outcomes compared with traditional instruction [14]. These findings support the integration of simulation not merely as a supplementary tool, but as a foundational component of surgical curricula [5, 15].

## **MODALITIES OF SIMULATION IN GENERAL SURGERY**

### **Low-Fidelity and Task-Based Simulation**

Low-fidelity simulators, including box trainers and bench models, remain essential for foundational skills such as knot tying, suturing, and basic laparoscopic dexterity [16–19]. Despite their simplicity, these platforms are highly effective when embedded within structured curricula and accompanied by expert feedback [20].

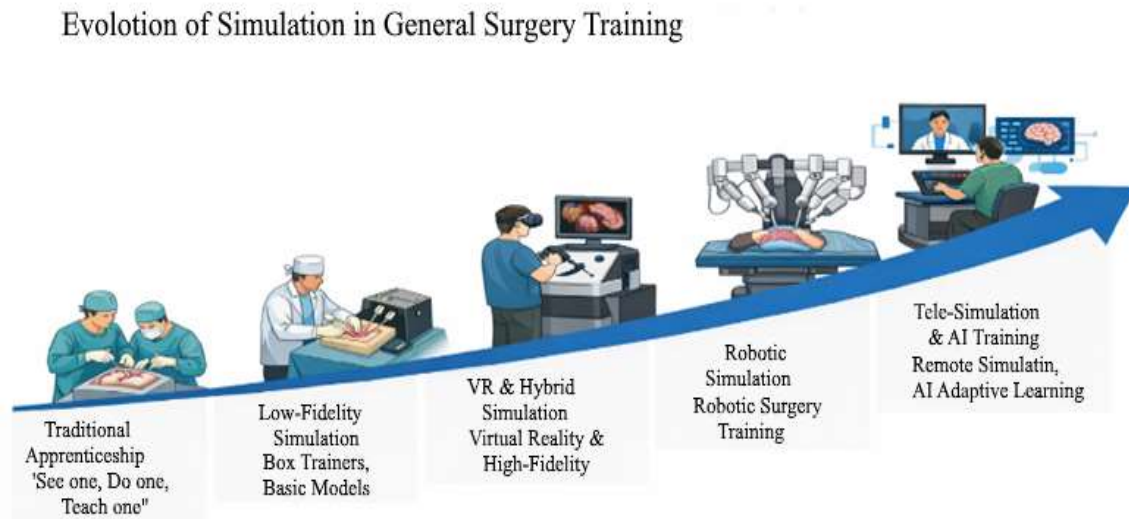
### **Virtual Reality Simulation**

VR simulators provide immersive environments that replicate anatomical variability, procedural steps, and intraoperative challenges [6]. Multiple studies have demonstrated that VR training improves operative performance in laparoscopic cholecystectomy, colorectal surgery, and advanced minimally

invasive procedures [6, 7]. Objective metrics, such as economy of motion, error rates, and task completion time, enable standardized assessment across trainees [5].

### Augmented and Mixed Reality

AR and mixed reality systems overlay digital information onto physical environments, enhancing anatomical orientation and procedural understanding [8]. Although still evolving, these technologies show promise in bridging the gap between simulation and live surgery, particularly for complex anatomical procedures (Figure 1) [8].



**Figure 1.** Evolution of simulation in general surgery training.

Schematic depiction of progression from apprenticeship and low-fidelity task trainers to VR, hybrid simulation, robotic simulation, tele-simulation, and AI-enabled adaptive systems

### Validation, Assessment, and Transfer to Clinical Performance

A major strength of simulation-based education lies in its capacity for objective assessment. Validated tools, such as global rating scales, procedure-specific checklists, and motion analysis metrics, have been widely adopted in general surgery training [11, 12]. Importantly, multiple studies have demonstrated that simulation-acquired skills translate into improved intraoperative performance and reduced complication rates [6, 13, 14].

Despite this evidence, variability in validation standards across simulators and institutions persists [5]. Linking simulation-derived performance data with real-world clinical outcomes remains a key priority for strengthening educational accountability [20].

### Robotic Surgery Simulation in General Surgery

Robotic platforms are increasingly utilized in general surgical procedures such as ventral and inguinal hernia repair, colorectal resections, foregut surgery, and bariatric surgery [15, 16]. Robotic simulators reproduce console ergonomics, camera clutching, wristed instrumentation, depth perception, and multi-arm coordination, allowing structured skills acquisition before patient exposure [15]. Simulation-based robotic curricula have been shown to shorten learning curves, reduce operative time, and decrease technical errors, particularly during early adoption phases [16]. Consequently, many institutions mandate simulation-based credentialing prior to independent robotic practice.

## SIMULATION ACROSS THE SURGICAL TRAINING CONTINUUM

### Undergraduate Medical Education

Simulation is increasingly integrated into undergraduate medical curricula to introduce procedural skills, applied anatomy, and clinical reasoning in controlled environments [2, 3]. Early exposure improves learner confidence and preparedness for clinical clerkships while minimizing patient risk [4].

### Residency and Fellowship Training

At the postgraduate level, simulation supports acquisition of advanced technical skills, crisis management, and team communication [5, 11]. Specialty-specific curricula in laparoscopy, endoscopy, trauma, and robotic surgery align with CBME milestones and outcome-based assessment [11, 12].

### Continuing Professional Development

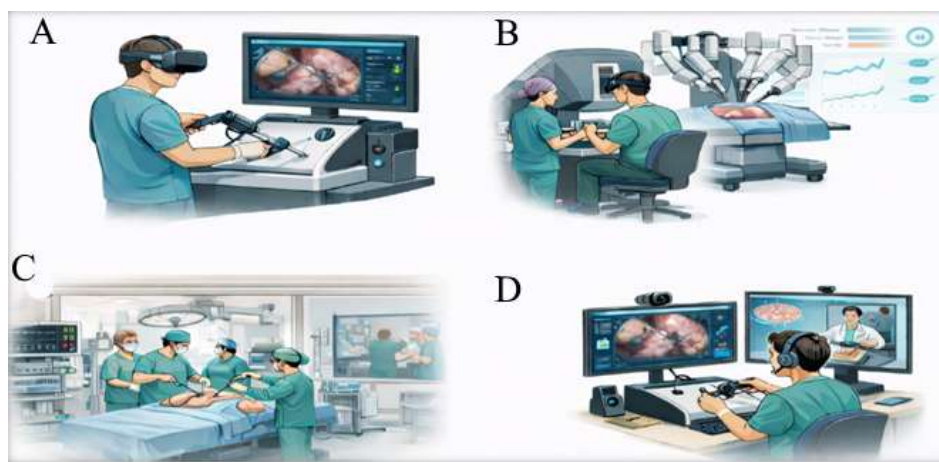
Simulation is increasingly used for maintenance of certification, skill refreshment, and safe adoption of novel technologies among practicing surgeons [9, 16].

### Team Training and Non-Technical Skills

High-fidelity simulation provides a robust platform for training non-technical skills such as communication, leadership, situational awareness, and decision-making [9]. Team-based simulation has been associated with improved operating room efficiency and reduced preventable adverse events, particularly in emergency general surgery [11].

### Tele-Simulation and Global Surgery Education

Tele-simulation enables remote instruction, supervision, and assessment, expanding access to high-quality surgical education in geographically remote and resource-limited settings [17]. Its adoption accelerated during the COVID-19 pandemic and has since evolved into a sustainable model for distributed surgical training and mentorship (Figure 2) [17, 18].



**Figure 2.** Contemporary simulation modalities in general surgery training.

Composite illustration demonstrating key domains of modern simulation-based surgical education. (A) Virtual reality-based laparoscopic simulation enabling immersive psychomotor skills training with real-time performance metrics. (B) Robotic surgery simulation depicting console ergonomics, multi-arm coordination, and supervised skills acquisition prior to live operating. (C) High-fidelity mannequin-based team simulation in a mock operating room environment, emphasizing procedural execution, crisis management and interprofessional communication. (D) Tele-simulation platform illustrating remote mentoring and assessment, facilitating distributed training and capacity building in resource-limited and geographically remote settings.

## LOWER-MIDDLE-INCOME COUNTRIES (LMIC) PERSPECTIVE: SIMULATION IN RESOURCE-CONSTRAINED GENERAL SURGERY TRAINING

### Regulatory Context: NMC and Competency-Based Training

In majority of the LMIC, postgraduate surgical training is regulated by their Medical Commission, which mandates competency-based medical education and institutional skills laboratories [19]. Simulation supports standardized skill acquisition and objective assessment within these frameworks [2, 11].

### **Skills Laboratories and Frugal Simulation Models**

Most LMICs employ low-cost box trainers, suturing stations, and basic laparoscopic simulators [11, 19]. Indigenous and frugal innovations, including locally fabricated and 3D-printed models, have demonstrated measurable improvements in technical performance among general surgery residents [11, 20].

### **Emergency and Essential General Surgery Training**

Simulation is particularly valuable for training in emergency conditions common in LMICs, including perforation peritonitis, bowel obstruction, and abdominal trauma [18]. Scenario-based simulation improves decision-making and team coordination in high-acuity settings [11].

### **Cost-Effectiveness and Scalability**

Low- to medium-fidelity simulation, when paired with structured curricula and expert feedback, achieves outcomes comparable to high-fidelity systems for core general surgery skills [20]. Regional hubs, mobile labs, and tele-mentoring enhance scalability [17, 18].

## **CHALLENGES AND LIMITATIONS**

Key challenges include cost, infrastructure requirements, faculty development, and heterogeneity in validation standards [5, 9]. Demonstrating long-term patient-level outcomes remains a priority, particularly in resource-limited environments [20]. Despite strong evidence supporting its educational value, widespread implementation of simulation-based training in general surgery faces several challenges. One of the most significant barriers is cost. High-fidelity simulators, virtual reality platforms, and robotic training systems require substantial initial investment, ongoing maintenance, and software upgrades, which may limit adoption, particularly in resource-constrained institutions [5, 11, 20]. Even in well-resourced centres, competing priorities for funding can restrict the scale and sustainability of simulation programs.

Infrastructure and logistical requirements represent additional constraints. Dedicated simulation spaces, technical support staff, and protected time for both trainees and faculty are essential for effective implementation [9, 11]. In many training programs, especially in low- and middle-income countries (LMICs), limited physical space and high clinical workload reduce opportunities for structured simulation-based learning [18, 19]. As a result, simulation is often underutilized or relegated to sporadic workshops rather than being integrated longitudinally into curricula.

Faculty development remains a critical yet frequently overlooked challenge. Effective simulation-based education requires trained faculty who can provide structured feedback, conduct objective assessments, and align simulation activities with curricular goals [3, 11]. Lack of formal training in simulation pedagogy and assessment methods can compromise educational impact and consistency across institutions.

Another limitation relates to variability in validation and assessment standards. Although numerous simulators and assessment tools exist, not all have been rigorously validated for educational effectiveness or transferability to clinical performance [5]. The absence of universally accepted benchmarks complicates comparison across programs and weakens the case for regulatory or credentialing mandates.

Finally, evidence linking simulation training to long-term patient-level outcomes remains limited. While improvements in technical performance and short-term operative metrics have been

demonstrated, large-scale studies correlating simulation exposure with sustained reductions in morbidity and mortality are scarce [14, 20]. Addressing these challenges will be essential to ensure that simulation-based education achieves its full potential in advancing general surgery training and patient safety.

### **FUTURE DIRECTIONS**

Future advances are expected in artificial intelligence-driven coaching, immersive multi-user virtual operating rooms, predictive competency modelling, and integration of simulation metrics with clinical outcomes [6, 8]. The future of simulation-based education in general surgery will be shaped by the convergence of digital technologies, educational theory, and evolving health system demands. Artificial intelligence (AI)-enabled simulation platforms are expected to play an increasingly central role by providing automated, objective feedback based on motion tracking, error recognition, and procedural sequencing [3, 6]. Machine learning algorithms can analyse large datasets generated through repeated simulation encounters to identify individual learning curves, predict performance gaps, and personalize training pathways, thereby strengthening competency-based medical education models [2, 5].

Extended reality technologies, including immersive virtual reality, augmented reality, and mixed reality, are likely to evolve toward highly realistic, anatomically precise virtual operating rooms [8]. The development of multi-user simulation environments will enable simultaneous participation of trainees, faculty, anaesthesiologists, and nursing staff, facilitating team-based rehearsal of complex procedures and intraoperative crisis scenarios [9, 11]. Integration of patient-specific imaging data into simulation platforms may further allow preoperative rehearsal for complex general surgical cases, improving operative planning and intraoperative decision-making [6, 8].

Another important future direction is the integration of simulation-derived performance data with real-world clinical outcomes. Linking simulator metrics with operative performance, complication rates, and patient safety indicators will strengthen validity evidence and support broader institutional and regulatory adoption [5, 14]. Such data integration may also assist credentialing bodies in defining objective benchmarks for certification, re-certification, and safe adoption of new surgical technologies, including robotics [11, 16].

From a global surgery and low- and middle-income country (LMIC) perspective, future innovation must prioritize affordability, scalability, and contextual relevance [18]. Frugal simulation models, low-cost haptic devices, and open-source digital platforms will be essential for expanding access beyond well-resourced academic centres [20]. Tele-simulation and remote proctoring are expected to mature further, enabling longitudinal mentorship, faculty development, and equitable dissemination of surgical expertise to geographically remote and resource-constrained regions [17, 18].

Finally, faculty development will remain a critical determinant of successful implementation of advanced simulation technologies. Educators must be trained not only in simulator operation but also in interpreting performance analytics, delivering high-quality feedback, and integrating simulation meaningfully into curricula [3, 11]. As simulation continues to evolve from a supplementary educational tool to an integrated training ecosystem, its alignment with surgical practice, patient safety priorities, and health system needs will define the next phase of general surgery education.

### **CONCLUSION**

Simulation has become an indispensable pillar of modern general surgery education. When aligned with educational theory and regulatory frameworks, it enhances surgical competence, patient safety, and global equity in training.

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