Simulation in Medical Education: History, Applications, and Effectiveness

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ABSTRACT

Introduction: Simulation-based training (SBT) has long played a role in health care education, evolving from rudimentary anatomical models to sophisticated digital platforms. Over time, simulation to include life-like mannequins, standardized patients, and immersive virtual environments, significantly enhancing the ability to teach clinical skills, communication, and decision-making in safe, controlled settings. As medical education continues to adapt to new challenges, simulation remains a cornerstone for preparing health care professionals through realistic and experiential learning.

Objectives: This review examines the evolution and current applications of simulation in medical education, highlighting its integration within military and civilian training environments. It describes major simulation modalities, reviews evidence supporting their effectiveness, and evaluates commonly used assessment tools. The review also outlines potential future directions for simulation-based education in response to the evolving needs of modern health care.

Methods: Relevant literature was identified through searches of PubMed and other academic databases. Articles were selected based on their relevance to the review objectives, including the historical development of simulation, its applications in diverse educational settings, and emerging technologies shaping the field.

Results: SBT has been widely adopted across all levels of health care education – from medical and nursing schools to residency programs and continuing professional development. It enhances technical skills, clinical reasoning, teamwork, and communication in structured environments. Civilian and military programs alike benefit from simulation's ability to replicate complex, high-stakes clinical scenarios. However, measuring its direct impact on clinical performance and patient outcomes remains challenging.

Conclusions: SBT is an essential component of modern medical education, enhancing clinical skills and helping bridging the gap between knowledge and practice. As technology advances, simulation offers new opportunities for personalized and scalable learning. Moving forward, educators must implement these innovations thoughtfully, maintaining a focus on empathy and patient-centered care.

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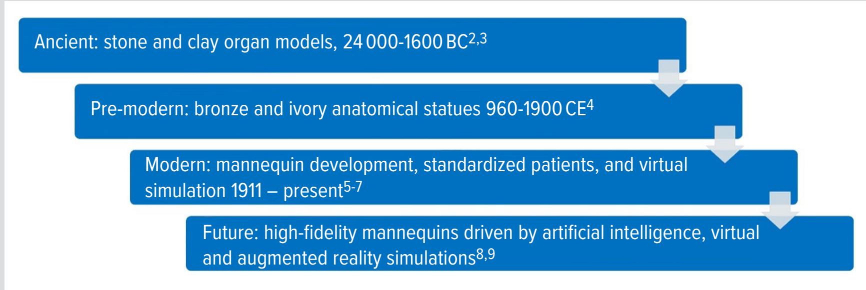
INTRODUCTION

Medical education has undergone significant evolution, driven by the increasing complexity of health care and the demand for highly skilled professionals. As required competencies broaden to include both technical procedures and essential nontechnical abilities such as communication, the need for effective, scalable, and resource-conscious training methods has never been greater. This demand is amplified by growing medical school class sizes, increasing physician workforce needs, and competition for limited clinical training spaces across health care disciplines.

Traditionally, medical training followed an apprenticeship model in which students learned by observing and participating in patient care under supervision. While valuable, this model is limited by inconsistent clinical exposure and inherent risk to patient safety.[1]

In response, simulation-based training (SBT) has emerged as a transformative tool in medical education. By providing realistic, immersive experiences in a controlled environment, simulation enables learners to develop and refine technical and nontechnical skills before applying them in high-stakes situations. It is far from ideal for a provider's first exposure to high-risk procedures – such as cricothyrotomy or pericardiocentesis – to occur on a critically ill patient. Through advanced modalities, including high-fidelity mannequins, virtual reality, and standardized patients, learners can safely build confidence, improve clinical competence, and enhance preparedness for the demands of modern health care.

Figure. Evolution of Medical Simulation



BACKGROUND AND HISTORY OF SIMULATION IN MEDICAL EDUCATION

SBT has ancient origins, with stone carvings of human forms dating back to 24 000–22 000 BC and Babylonian clay liver models (1900–1600 BC) likely used for medical interpretation. In 6th-century BC China, the philosophical founder of Taoism, Lau Tzu, described wooden and leather automation figures, suggesting early mechanical simulation. More than 2500 years ago, clay and leaf models were used in India to simulate nasal reconstruction, marking the first recorded surgical simulation.[2,3]

During the Song Dynasty (960–1279 CE), life-sized bronze statues with anatomical features helped teach acupuncture and surface anatomy. Ivory female figurines used in the Ch'ing Dynasty (1644–1912 CE) enabled male physicians to study female anatomy as direct examinations of were prohibited.[4] In the 18th century, Giovanni Antonio Galli created a glass uterus model to train midwives, representing the first documented modern medical simulation. Around the same time, early attempts to simulate cardiovascular physiology emerged, reflecting increasing interest in realistic medical training tools.[3]

As illustrated in the Figure, the early 20th century brought major advances in medical simulation, particularly the widespread use of mannequins. Although Resusci Anne is widely recognized, modern mannequin-based simulation can be traced to Mrs Chase, created in 1911 by toymaker Martha Chase at the request of Harford Hospital Training School to train nursing staff to dress and move patients. An updated version, Arabella–created by Chase in 1914–incorporated features such as the ability to simulate arm injections, sparking growth in the practice of simulation.[5] The 1960s introduced more advanced models, including Resusci Anne with a compressible chest mechanics for the practice of CPR[6] and the SIM 1 mannequin, which provided real-time feedback to medications, adjustable pupils, palpable pulses, simulated respirations, and a jaw that opened.

Another pivotal development was the introduction of actors serving as standardized patients. Although not widely accepted initially, standardized patients are now integral to "hands-on" education and assessment. Beginning in 2004, the United States Medical Licensing Examination (USMLE) Step 2 Clinical Skills examination formally incorporated standardized patient encounters.[7]

Virtual simulation also emerged in the early 2000s. Second Life, a virtual simulation, enables learners to create avatars and interact with virtual patients, offering a low-stakes environment where to practice skills such as obtaining consent, treating patients, and managing complications.[8] Virtual simulation's flexibility reduces reliance on physical equipment and supports simultaneous use by multiple learners. The widespread use of virtual reality (VR) in today's environment could greatly impact medical education and will be discussed further.

The history of medical simulation demonstrates unique innovation and an intense desire to improve medical training for the benefit of patients. However, progress may reach a plateau. The traditional model of "see one, do one, teach one," long associated with medial training and popularized in reality medical TV–has become outdated. A key reason–particularly in surgical specialties–is the necessity for more repetition with less time and less coaching. Current trainees face new challenges, including competition with fellows, decreased duty time, and an ever-increasing focus on research. As training needs evolve, perhaps a more appropriate training model may be "prepare, simulate, provide."[9]

CURRENT USES OF SIMULATION IN MEDICAL AND HEALTH PROFESSIONS TRAINING

Simulation plays a significant role in current medical and health professions training by offering a controlled environment for trainees to engage with realistic clinical scenarios in a low-risk setting. SBT is utilized in medical school, residency, and fellowship, as well as in allied health and military training, to improve confidence, clinical reasoning, team efforts, and technical skills while bridging a gap between theory and direct patient care. Its use in medical training and continuing education has been associated with improved clinical outcomes and patient safety.

In 2011, the Association of American Medical Colleges reported that 68% of medical schools had incorporated simulation-based education into their curricula.[10] One of the earliest exposures for medical students often occurs during basic life support training, which uses low-fidelity manikins to teach students how to use an automated external defibrillator (AED), relieve an obstructed airway, and perform cardiopulmonary resuscitation (CPR). Additionally, SBT is integrated into preclinical years through standardized patients and high-fidelity mannequins to practice history taking, physical examination techniques, and clinical reasoning. These early simulated experiences help reduce medical students' anxiety, enhance confidence, and improve communication and critical thinking skills.[11] Simulation-based learning also reinforces didactic material and improves performance on standardized examinations. In a 2020 study of an 8-week curriculum incorporating high-fidelity simulation scenarios, students improved by an average of 18% on postcurriculum examinations compared with precurriculum data.[12]

Beyond undergraduate training, the Accreditation Council for Graduate Medical Education (ACGME) recommends integration of simulation-based curricula into residency and fellowship programs. Procedural simulation is widely used in specialties including emergency medicine, general surgery, and internal medicine, where residents practice specialty-specific skills–including code management, endoscopy, and catheterization--using high-fidelity mannequins and task trainers.[13–15] Crisis resource management training enables the practice of nontechnical skills, such as communication, situational awareness, prioritization, and resource utilization. By simulating high-acuity, low-frequency events, these programs offer a controlled setting to refine these skills.[16]

The effectiveness of simulation in graduate medical education extends beyond skill rehearsal. One study found statistically significant gains in internal medicine residents' confidence performing procedures such as arterial and central line placement and thoracentesis after a simulation program.[17] Another study showed that a virtual case-based simulation improved residents' clinical decision-making and diabetes management skills–including insulin use, glucose interpretation, and lipid management.[18]

Simulation is similarly utilized in allied health training. In clinical nursing education, high-fidelity mannequins replicate patient conditions and responses to interventions such as medication administration or recognition of patient deterioration. Partial task simulators, such as isolated limbs, support repeated practice of technical skills including intravenous catheterization and CPR.[19] Pharmacy programs have also integrated simulation through software programs and virtual reality platforms, enabling students to practice dispensing skills and error prevention.[20] Together, these approaches underscore the essential role of SBT in preparing health professions learners for clinical practice.

Simulation is also used in the clinical workforce for continuing education and skills maintenance. Health care providers may experience skill decay–the loss of a previously acquired skill–after periods of nonuse due to leaves of absence, changes in specialty or the infrequency of certain procedures. Refresher training helps mitigate skill decay and its impact in the clinical environment.[21] This is particularly important for time-sensitive, life-saving skills. For example, high-quality CPR is critical in cardiac arrest, yet studies show that CPR skills deteriorate within 6 to 12 months after training.[22] The American Heart Association developed the Resuscitation Quality Improvement (RQI) program, which uses a mobile simulation station with real-time feedback on compression rate, depth, and fraction. RQI training is delivered quarterly to health care providers to foster retention and improvement of CPR skills.[23]

Simulation also plays a vital role in military medical education, preparing personnel for high-pressure, unpredictable scenarios that traditional methods–such as lectures, e-learning, live tissue training, and animal models–cannot fully replicate.[24] High-fidelity simulations provide realistic exposure that helps trainees develop technical skills, decision-making, and critical thinking under conditions that mirror battlefield medicine.

The US Army developed a game-based simulation to enhance Tactical Combat Casualty Care (TCCC) training, allowing soldiers assume the role of a combat medic operating in a deployed environment. Such interactive training methods are especially engaging for younger learners, who grew up with video games, thereby increasing their motivation to learn. Soldiers reported that they enjoyed the training and found it beneficial, and posttraining test scores were comparable to those who received traditional TCCC instruction.[25]

Simulation also strengthens teamwork, communication, and coordination–skills essential to effective care in deployment settings. Studies show improvements in trauma care protocols, emergency management, and response to chemical exposures. Repeated exposure to realistic scenarios reinforces muscle memory and acclerates decision-making, enabling military medical personnel to respond instinctively and effectively in real-world crises.

Overall, simulation-based training has become indispensable across the spectrum of health care education–from early medical and health professions instruction to specialized military preparation. By providing realistic, hands-on experiences in a safe and controlled setting, simulation enhances technical proficiency, critical thinking, communication, and teamwork while reducing risks associated with real-world practice. Its role in mitigating skill decay and maintaining clinical readiness ensures that health care providers–whether in civilian hospitals or on the battlefield–are equipped to deliver timely, effective, and life-saving care. As technology and educational methods continue to evolve, simulation will remain a cornerstone of training strategies aimed at improving provider competence and patient outcomes.

EVALUATING THE EFFECTIVENESS OF SIMULATION-BASED TRAINING

The evaluation of simulation use in education is critical to ensure that the intervention is beneficial for the learner and, ultimately, for patients. Evaluation also provides feedback and supports improvement of the intervention to maximize effectiveness and outcomes.

One commonly used model for evaluating educational interventions is the Kirkpatrick Model. This model been used across disciplines to assess training using measurable outcomes. In health care, it serves as a valuable tool for determining training effectiveness and facilitating improvements that enhance learner satisfaction, confidence, and impact. The Kirkpatrick Model consists of 4 levels: reaction, learning, behavior, results.[26] Level 1 (reaction) assesses student engagement and satisfaction, typically via post-simulation surveys evaluating the quality of the intervention and learners' perceptions. Level 2 (learning) refers to the knowledge or skills gained during the simulation, and can be measured through pre- and post-assessments using knowledge-based questions or student teachbacks. Learner confidence is also measured at this level. Level 3 (behavior) evaluates the application of learned material in the clinical environment. At level 4, results are measured. This typically refers to the simulation's impact on patient outcomes systemically. In medical education, levels 1 and 2 – and sometimes level 3 – are targeted most frequently when developing simulation crurricula.

Another framework used to evaluate clinical competence is the Miller Pyramid, developed by George Miller to shift assessment away from knowledge-based examinations. This hierarchical model consists of 4 levels. The base level is knowledge, which assesses knowledge acquisition through traditional testing, similar to level 2 of the Kirkpatrick Model. The second tier is the application of knowledge. The third level represents clinical skill competency and is best measured through simulation and standardized patient encounters. The top tier reflects clinical performance assessed through direct observation of trainees in the clinical setting.[27] Simulation-based education aims to support progression toward the top tiers of Miller's pyramid, as the hands-on nature of simulation learning allows for the development of the trainee's clinical skillset and performance in the clinical setting.

Objective Structured Clinical Examinations (OSCEs) are widely used in health professions education to assess the third tier of Miller's pyramid: clinical competence.[27] During an OSCE, students interact with a standardized patient in simulated clinical setting and are evaluated on specific skills, often presented as a checklist.[28] These skills range from communication and professionalism to procedural skills and clinical reasoning. Students receive formative feedback after completing the examination.

Although simulation has proven useful in medical education, evaluating its effectiveness remains challenging. Most studies focus on Kirkpatrick's levels 1 and 2 for evaluation, because learner satisfaction and knowledge acquisition can be readily assessed using surveys and examinations. However, levels 3 and 4 are more difficult to evaluate, raising concerns about the transferability of skills to patient care.[6] Additionally, it is difficult to directly attribute improvements in patient outcomes to simulation-based interventions.

CURRENT AND FUTURE OPPORTUNITIES FOR SBT

The future of SBT in medical education is rapidly evolving, driven by emerging technologies such as artificial intelligence (AI), virtual reality (VR), and augmented reality (AR). These innovations enhance the realism, interactivity, and accessibility of training environments.

AI has demonstrated significant benefits in medical education. AI-powered problem-based learning platforms have been shown to improve students' comprehension of clinical diseases, promoting deeper understanding and retention. In an ophthalmology clerkship study, students taught about congenital cataracts via an AI diagnostic simulation reported overall satisfaction with the training and had significantly higher posttest scores than those taught with a traditional lecture-based format.[29] Additionally, integration of AI with surgical simulation systems has also resulted in advanced training tools that offer objective feedback on surgical techniques—allowing for personalized learning and skill refinement.[30]

Beyond skill acquisition, AI is transforming how institutions support student well-being. AI-based monitoring tools are now being used to track mental health and academic performance, providing educators with real-time insight and enabling timely interventions.[31] These capabilities suggest that AI will not only enhance SBT outcomes but also foster more supportive and adaptive learning environments.

VR continues to transform medical education by offering interactive, immersive platforms for clinical training. Using head-mounted displays, such as the Oculus Rift and HTC Vive, students can engage with virtual wards, patients, colleagues, and family members in realistic, case-based scenarios. These simulations allow learners to practice taking patient histories, performing physical examininations, making diagnoses, and delivering treatments – all within an emotionally dynamic and adaptable hospital environment.[32]

A systematic review by Mahmood et al analyzing 21 randomized controlled trials highlighted the effectiveness of VR-based simulation in endoscopy training. With improvements observed in technical skills, procedural advancement, nontechnical competencies, and patient comfort – particularly during early learning stages.[33] However, VR did not fully replace traditional teaching methods. Feedback remained a critical component of effective learning, underscoring the need for integrated instructional support.

Integrating VR training into medical curricula offers potential cost and time savings. Compared with simulation methods that require physical equipment, space, and personnel, VR delivers on-demand clinical experiences with fewer resources and at lower operational costs. Institutions benefit from scalable, repeatable simulations that can be conducted without the logistical demands of setting up physical labs or scheduling standardized patients. VR systems also allow students to engage in self-paced learning, making better use of limited training hours. With VR kits currently costing $2000 to $2500 and prices expected to decline as technology advances, VR is becoming an increasingly accessible option.[32]

AR is also emerging as a valuable tool in medical education, particularly in surgical training. In a randomized simulation trial involving final-year medical students applying to surgical residencies, AR technology was used to train participants in total hip arthroplasty. One group trained using an AR headset providing live holographic orientation feedback, while a control group received traditional one-on-one instruction from a hip arthroplasty surgeon. After 4 weekly sessions, both groups demonstrated comparable accuracy, suggesting that AR can effectively support the acquisition of motor skills in a self-directed setting.[34] These findings underscore AR's potential as a flexible and scalable supplement to expert instruction..

BARRIERS TO OVERCOME

While there are exciting developments in medical simulation, an important question demands answering: What is the cost? High-fidelity medical simulation programs may require substantial upfront investment, maintenance costs, and the opportunity cost of training staff to use equipment.[9] Smaller programs with limited resources may be unable to obtain cutting-edge simulation equipment, potentially exacerbating educational and patient outcome disparities. Additionally, due to the large initial cost, training requirements, and mass standardization of simulation education, large organizations may struggle to keep up with continuous changes in surgical and procedural techniques.

Another potential limitation is the risk of compromising students' psychological safety. Psychological safety refers to the learner's belief that the simulation environment is a safe space for risk-taking – such as asking questions, expressing uncertainty, and making mistakes – without fear of being humiliated or penalized. Maintaining psychological safety is important because it encourages learner engagement and improves learning outcomes. Facilitators can promote psychological safety by orienting learners to the environment and equipment, clearly stating learning objectives, establishing confidentiality agreements, and offering constructive feedback.[34,35] These safeguards should be upheld in simulation exercises to optimize learning.

Perhaps the most important consideration involves patient experience. Some may fear that increasing simulation will distance trainees emotionally from patients. Because simulations – whether virtual or through standardized patients – takes place in a low-stakes environment, it may remove most or all of the human elements central to the doctor-patient relationship.[36] Thus, as simulation in medical education continues to expand, systems should be in place to monitor whether patients are satisfied with the relationships that are formed with simulation-trained physicians.

CONCLUSIONS

Exciting opportunities lie ahead for physician education and training. Advances in simulation are changing the dated training model of "see one, do one, teach one" to "prepare, simulate, provide." SBT is a vital tool for medical education, fostering clinical competence, building learner confidence, and supporting skill development in a controlled, low-risk environment. Grounded in educational frameworks such as Miller's Pyramid and the Kirkpatrick Model, SBT helps bridge the gap between theoretical knowledge and clinical application. Emerging technologies – including artificial intelligence, virtual reality, and augmented reality – have expanded the reach and capability of simulation, offering scalable, cost-effective, and personalized learning opportunities. However, challenges persist in evaluating long-term outcomes, addressing financial barriers, and ensuring equitable access across institutions. As simulation continues to evolve, medical educators must balance technological innovation with the preservation the humanistic elements of patient care, ensuring that future physicians are both technically skilled and relationship-centered.

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