REVIEW ARTICLE

Current Status and Prospects of Simulation-based Medical Education in Ultrasound

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Abstract: Simulation-based ultrasound education (SBUE) is an important component of ultrasound education and prepares learners before they begin clinical practice. It has gradually evolved from single-skill training centered on phantoms and task trainers into an educational system that emphasizes clinical contexts, continuous assessment, and the development of clinical competence. This review summarizes the developmental history, major modalities, educational implementation and evaluation, current limitations, and future directions of SBUE. Major SBUE modalities include physical models, virtual simulation, standardized patients (SPs), scenario-based simulation, and telesimulation. Courses should be designed around clinical tasks, competency objectives, and available resources, with staged feedback and continuous assessment to improve performance on specific tasks over both the short and long term. Evidence that these gains translate into clinical performance and patient outcomes remains limited. Future studies should focus on developing a competency-based system with refined tiered frameworks and longitudinal assessment pathways, as well as exploring applications of artificial intelligence and other emerging technologies in ultrasound simulation education.

Key words: Simulation-based medical education; Simulation-based ultrasound education; Ultrasound education; Clinical competence; Competency assessment

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Ultrasound imaging is now integrated into many areas of modern clinical practice, ranging from trauma assessment in the emergency department and hemodynamic monitoring in the intensive care unit to vascular access and nerve blocks in anesthesiology and fetal screening in obstetrics. With its distinctive advantages of being noninvasive, real-time, portable, and repeatable, ultrasound has evolved from a specialized imaging technique into a cross-disciplinary tool in bedside and non-bedside practice [1,2]. Ultrasound is now used not only by imaging specialists but also by clinicians in emergency medicine, critical care, anesthesiology, internal medicine, and general medicine. The acquisition of ultrasound competency has become an increasingly recognized goal in undergraduate and postgraduate medical education [2,3].

Ultrasound examination relies on hands-on scanning, hand-eye coordination, anatomical knowledge, and clinical interpretation. Traditional bedside "master-apprentice" teaching may be limited by patient-safety and ethical concerns, inconsistent exposure to the disease spectrum, variability in preceptor competence, and subjective evaluation of teaching effectiveness [4,5]. Simulation-based medical education (SBME) allows trainees to

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learn ultrasound theory, operational skills, clinical reasoning, and emergency management in a controlled environment without exposing patients to the risks of early practice; it also permits repeated practice and immediate feedback. This approach is referred to as simulation-based ultrasound education (SBUE). Simulation-based training with deliberate practice has been associated with better performance in selected clinical skills than traditional teaching or pretraining baselines [6]. Studies of ultrasound training in transesophageal echocardiography (TEE), obstetric ultrasound, lung ultrasound, and specific technologies such as extended reality suggest that SBUE is an important adjunct [4,7-9].

Few comprehensive reviews have addressed SBUE across specialties and technical platforms. This review examines five aspects of ultrasound simulation education: its historical evolution, major modalities, educational implementation and outcome evaluation, current limitations, and future directions. It aims to clarify the field and support the normalization, standardization, and modernization of ultrasound simulation training.

In this narrative review, we searched PubMed/MEDLINE, Web of Science, the Cochrane Central Register of Controlled Trials (CENTRAL), and Embase for publications from database inception through September 10, 2026, using combinations of terms related to ultrasound, simulation, education or training, phantoms, virtual reality, standardized patients, and telesimulation. We prioritized peer-reviewed English-language publications, including relevant systematic reviews, randomized trials, validation studies, and implementation studies. We excluded publications unrelated to ultrasound education, reports with insufficient information, duplicate publications, and technical descriptions without an educational component. Publications were selected for their relevance to the review topics; no formal risk-of-bias assessment was undertaken.

History of Simulation-based Ultrasound Education

SBME encompasses educational activities that use simulation methods to recreate clinical scenarios for teaching instead of real patients [10-12]. The application of simulation in medical practice dates back centuries [13]. Modern medical simulation began in the mid-20th century [10,13]. Resusci Anne, invented by Peter Safar and Åsmund Lærdal in 1960, pioneered skills training through simulation. With the development of high-fidelity mannequins, computer-based simulators, virtual reality systems, and specialty-specific task trainers, SBME gradually evolved into a more structured and evidence-informed field [12-14]. In 2003, Ziv et al. argued that simulation-based teaching constitutes an ethical imperative in medical education [12].

SBUE represents a specialized application of SBME in ultrasonography. It refers to teaching activities that use simulators, phantoms, standardized patients, computer and multimedia platforms to simulate human anatomy, selected physiological and pathological conditions, and clinical diagnostic and treatment scenarios. Learners can acquire skills through repeated practice in a risk-free environment and receive objective performance assessments [12,15,16].

Its technical origins can be traced to simple physical phantoms developed in the late 1990s. In 1997, Harvey et al. used turkey breast phantoms to train operators for ultrasound-guided breast core-needle biopsy [17]. In 2000, Knudson et al. introduced simulation technology into trauma ultrasound training, pioneering emergency trauma ultrasound education [18]. In the early 2000s, computer-based virtual imaging simulators emerged. In 2003, Terkamp et al. reported an evaluation study of abdominal ultrasound simulators [19]. In 2004, Maul et al. described the application of SonoTrainer, a transvaginal obstetric ultrasound simulator, and reviewed training systems of the same period, providing early evidence for the field [20]. In parallel, Heer et al. proposed an ultrasound training system based on the "virtual patient" concept [21].

Subsequently, simulation modalities continued to expand. In 2009, Girzadas et al. combined task trainers with high-fidelity mannequins to establish hybrid simulation models [22]. In 2011, Stather et al. validated endobronchial ultrasound (EBUS) simulators, extending ultrasound simulation into endoscopic subspecialties [23].

Principal Modalities of SBUE

The five principal SBUE modalities are physical models, virtual simulation, standardized patients, scenario-based simulation, and telesimulation. Each addresses different learning objectives. Their selection and combination depend on learner experience, task-related risks, and available resources. The principal educational emphases of the five modalities are summarized in figure 1.

Physical models, or phantoms, mimic the acoustic properties of human tissue so that learners can acquire ultrasound images and repeat procedures (Fig. 2). They are among the oldest and most widely used modalities, encompassing anatomical imaging models and task trainers for needle-based procedures. Commercial synthetic phantoms are available alongside locally made low-cost models using gelatin, agar, ballistic gel, biolog-

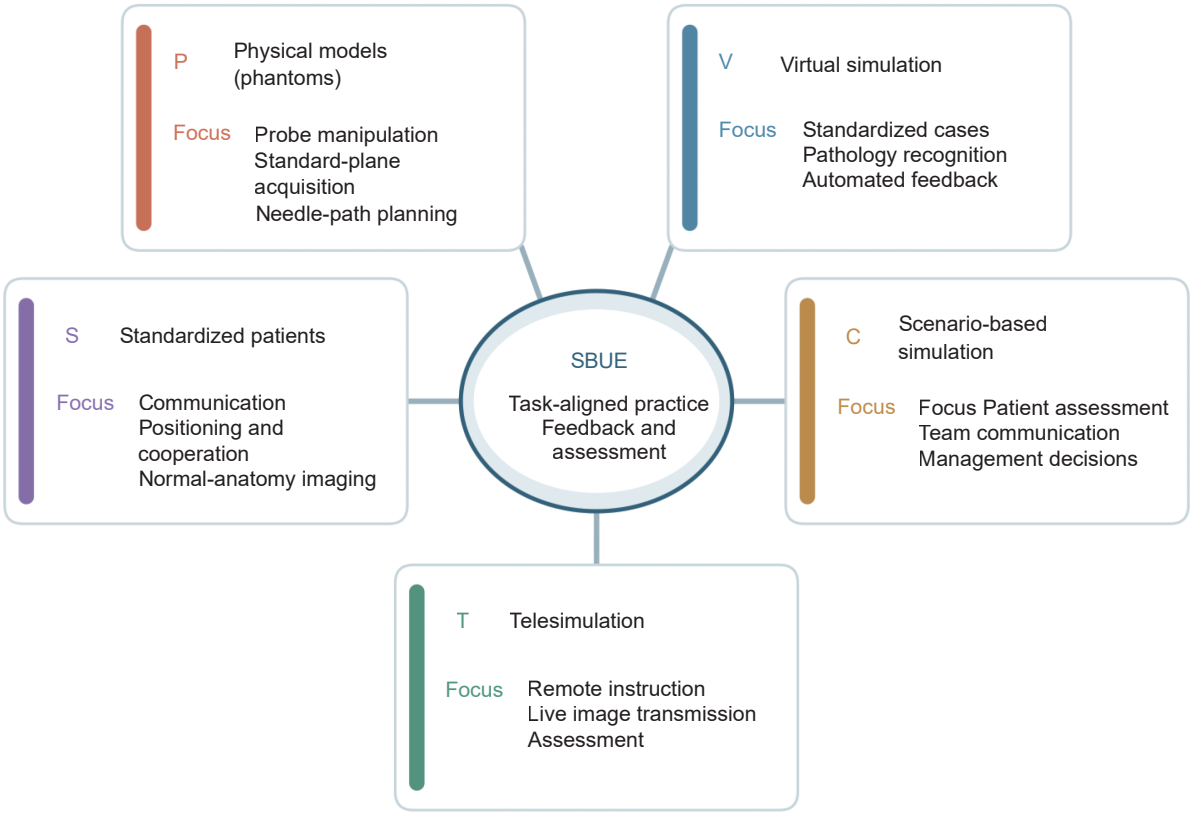


Figure 1 Principal modalities of simulation-based ultrasound education (SBUE). Physical models (or phantoms), virtual simulation, standardized patients, scenario-based simulation, and telesimulation provide complementary educational functions and may be selected or combined according to learning objectives, learner level, task risk, and available resources.

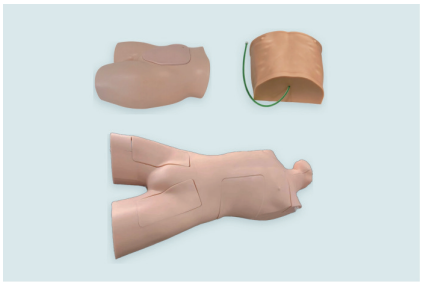


Figure 2 Physical models (phantoms) for simulation-based ultrasound education. The image shows regional task-specific phantoms and a whole-body model that support repeated scanning, anatomical visualization, and procedural skills training.

ical tissues, or three-dimensional (3D)-printed composite materials. Material choice involves a trade-off: gelatin and agar can approximate tissue acoustics but may have limited storage stability, whereas polyvinyl chloride (PVC) and polyvinyl alcohol (PVA) are more durable [24].

For novices, physical models are a common starting point for practicing probe manipulation, standard-plane acquisition, needle-path planning, and hand-eye coordination. Common applications include ultrasound-guided vascular access, nerve blocks, biopsies, and thoracic or abdominal punctures. In a randomized, double-blind controlled study, a homemade gelatin phantom and a commercial Blue Phantom did not differ significantly in ease of use, tissue-like visual appearance, or needle visualization, although some tactile and handling-related features differed. Homemade models may therefore be feasible in resource-limited settings [25]. A small randomized educational trial at one university reported that an agar-based phantom costing less than US$10 was non-inferior to a commercial model for improving self-reported procedural confidence [26]. Physical models nevertheless provide limited tactile feedback and represent anatomical variation and pathology only incompletely. The required level of fidelity depends on the learning objective: low-cost models may suffice for basic technical training, whereas recognition of complex pathology may require high-fidelity platforms or clinical practice.

Virtual simulation generates or reconstructs ultrasound images as learners move a simulated probe, updating the image in real time according to probe position and orientation (Fig. 3). High-fidelity virtual imaging simulators either reconstruct a three-dimensional anatomical environment from patient ultrasound datasets or use extended reality (XR) to create an immersive platform. Both typically include case libraries and automated feedback. Virtual reality (VR) allows immersive, interactive, and repeatable training [27], and high-fideli-

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Figure 3 Virtual simulation for obstetric ultrasound education. A tracked transducer is positioned on the abdomen of a virtual pregnant patient; green markers indicate scanning targets, and the simulator displays a corresponding fetal ultrasound image showing the fetus, amniotic fluid, and umbilical cord.

ty virtual imaging simulators can support standardized deliberate practice and formative assessment [16,28].

Studies of TEE illustrate reported educational gains. In a randomized study, novice operators who received simulator training achieved higher focused TEE examination-quality scores on patients than those who received lectures alone (75.6 vs. 55.9) [29]. The multicenter SIMULATOR randomized clinical trial enrolled 324 trainees at 42 teaching centers and found higher theoretical and practical test scores with simulation than with conventional training at 3 months [30]. A meta-analysis of 9 randomized controlled trials also found significant improvements in procedural skills and theoretical knowledge, with standardized mean differences of 0.81 and 1.61, respectively [31]. Simulator-based TEE training has shown benefits for theoretical knowledge and procedural performance, but evidence of broader and sustained transfer to clinical practice remains limited.

Standardized patients (SPs) may be either human or virtual [32,33]. A human standardized patient (HSP) is a trained individual who consistently portrays a specified medical history, symptoms, selected physical findings, behaviors, and emotional responses, whereas a virtual standardized patient (VSP) reproduces a standardized clinical encounter through a digital platform (Fig. 4). Both forms can support training in history taking and communication. HSPs also allow learners to practice the complete examination process in a realistic interpersonal setting, integrating technical performance with communication throughout the encounter [16]. When pathological findings are needed, an HSP may be combined with a phantom, pathology overlays, or high-fidelity scenario elements to create a hybrid simulation [22,34]. HSP-based training requires informed consent and careful attention to participant comfort; invasive procedures and repeated scanning likely to cause discomfort are better practiced using other simulation modalities [32].

Hybrid SP-based courses have been reported in medical education, including perioperative point-of-care ultrasound (POCUS) curricula [35]. A high-fidelity scenario combined with an ultrasound task trainer can support training and evaluation of endovaginal ultrasound skills [22]. These applications build on the established use of SPs in communication training, physical examination, and objective structured clinical examinations (OSCEs).

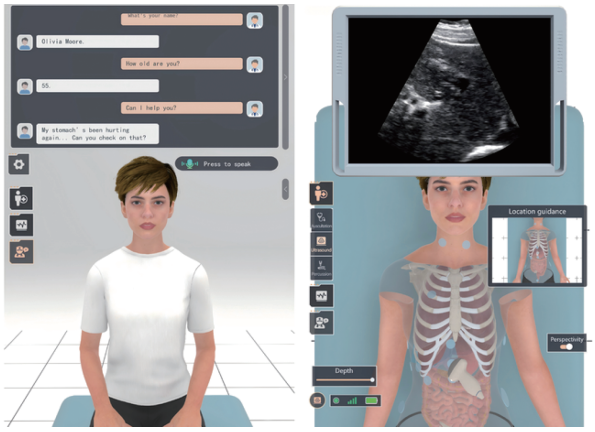


Figure 4 Virtual standardized patient (VSP) interface for history taking and simulated ultrasound examination. The left panel shows a digital patient–learner dialogue for history taking, and the right panel shows a virtual ultrasound module with probe-location guidance, anatomical visualization, and controls for imaging depth and viewing perspective.

Scenario-based simulation requires learners to use ultrasound within a complete clinical encounter, integrating scanning with patient assessment, team communication, and management decisions. Single-discipline exercises include resuscitative TEE and focused assessment with sonography in trauma (FAST). Multidisciplinary scenarios incorporate crisis resource management and team communication, often combining a high-fidelity manikin with a task trainer. These formats are suited to time-sensitive work in emergency medicine, critical care, anesthesiology, and perinatal care. Debriefing should follow prespecified learning objectives and address the clinical decisions surrounding an examination, as well as whether the intended image was obtained.

Scenario-based resuscitative TEE training has been evaluated for retention and transfer to practice. In one study, standard-plane acquisition and diagnostic accuracy remained stable 3 months after training in simulation-based assessments [36]. In a live-patient assessment after simulation training, 76.7% of 60 TEE views obtained by emergency medicine residents were acceptable, providing preliminary evidence of transfer to clinical practice [37]. A cardiac-arrest scenario course also significantly reduced learners' perceived barriers to TEE [38]. Scenario-based training may help learners move from simulated TEE practice to supervised examinations in patients.

Telesimulation connects geographically separated instructors and learners through live audio and video, remote image sharing, and online simulation platforms (Fig. 5). It includes real-time remote instruction, remote assessment and examination, and interactive systems supported by cloud platforms and 5G networks [39]. A simple local phantom can be paired with remote expert guidance and assessment to support instruction and feedback in resource-limited regions. Implementation requires adequate network connectivity and image quality, and data security should be verified before training. On-site supervision remains necessary for high-risk procedures.



Figure 5 Telesimulation for ultrasound education. A learner performs ultrasound scanning on a task-specific phantom while a camera, display, and network equipment support real-time image transmission and interaction with geographically remote instructors or participants.

Remote and on-site assessments showed high agreement in a study of remote ultrasound-guided regional anesthesia training [40]. In a randomized controlled trial of critical care ultrasound training delivered through a 5G cloud platform (n = 90), the remote group scored significantly higher than the online video group (88.4 ± 6.7 vs. 72.9 ± 10.8) and reported significantly higher satisfaction [41]. A Best Evidence Medical Education systematic review suggested that telesimulation could augment standard in-person simulation rather than serve only as a temporary substitute [42]. A systematic review of low-cost telesimulation in low- and middle-income countries found that it can improve knowledge and skills, but evidence on long-term behavioral and patient outcomes remains lacking [43].

Modality selection should follow the training need. Physical models provide accessible opportunities for repeated practice of basic scanning and needle skills. Virtual simulation provides standardized cases and controlled exposure to pathology, with automated feedback; SPs allow normal-anatomy scanning and authentic interpersonal interaction. Scenarios place ultrasound within clinical decisions and team care, whereas telesimulation extends teaching and assessment across geographical boundaries. These complementary uses guide how modalities are selected or combined for a given learning objective, learner level, task risk, and resource setting.

Educational Implementation and Evaluation

A simulation curriculum requires clear learning objectives, explicit competency standards, and an appropriate simulation modality. Image acquisition, ultrasound-guided procedures, image interpretation, and clinical decision-making call for different forms of practice and feedback [16,44]. The chosen simulation modality should be judged by how well it serves the learning objective, not by how technically advanced the simulator is [45].

The modality may vary with the task and available resources, but learners need repeated practice and timely feedback until their performance meets a defined standard. In a FAST simulator study, 23 of 25 novices reached the mastery standard, but the time and number of attempts varied [46]. A randomized extended focused assessment with sonography in trauma (eFAST) trial showed that residents who received mastery training earlier reached the standard for clinical technical performance sooner than those trained later [47]. A self-directed program based on scan counts did not establish that all learners had achieved competence [48]. These findings favor progression based on demonstrated performance rather than a fixed number of scans. After initial training, delayed reassessment can identify skills that need refresher practice [49].

Assessment should identify both what learners need to improve in practice and whether they have reached the expected level of competence. Simulator-generated metrics can provide immediate, standardized feedback during practice, but they require task-specific validity evidence before being used for competency decisions. A FAST validation study identified validity evidence for 34 of 55 built-in metrics [50], while 37 of 60 metrics in upper abdominal ultrasound distinguished novices from experts [51]. In simulated thyroid ultrasound, only 9 of 64 built-in metrics showed validity evidence, whereas the expert-rated Objective Structured Assessment of Ultrasound Skills (OSAUS) items distinguished novices from experts [52]. Automated metrics are useful for formative feedback when they have been validated for the relevant task and learner population. For high-stakes decisions about progression to clinical practice, they should not replace structured expert assessment.

Competency assessment should combine validated process metrics with expert evaluation of image acquisition and quality, interpretation, and the clinical decisions based on the findings [50,52-56]. For image interpretation, image-feature-based training improved beginners' thyroid ultrasound scores and interobserver agreement [57]. Direct observation is also needed to assess communication, patient interaction, and performance in complex clinical situations. The components included in

an assessment should reflect the course objectives and the risks associated with the clinical task. OSCEs provide a useful framework for integrating technical performance, communication, and the clinical application of ultrasound findings [35,56]. In resource-constrained programs, low-cost phantoms can support task-specific teaching and assessment [25,26].

Most SBUE studies have focused on immediate educational outcomes, typically measured as knowledge or task-specific performance during or shortly after training [31,58-64]. In obstetrics and gynecology, simulation-based ultrasound training was more effective than clinical training alone and theoretical teaching, with standardized mean differences of 0.84 and 1.20, respectively [58]. A meta-analysis of nine randomized TEE trials involving 268 participants similarly found large improvements in post-training skills and knowledge, with standardized mean differences of 0.81 and 1.61 [31]. These findings are consistent with a broader meta-analysis of 609 health-professions simulation studies, which reported large effects on knowledge and skills [65].

Few trials have examined whether these gains extend beyond the training environment. Simulator-trained novices performed higher-quality focused TEE examinations in intensive care patients than learners who received lecture-based training alone [29], and eFAST mastery training enabled residents to reach the required level of clinical performance earlier than those trained later [47]. Of 42 studies of ultrasound-guided procedural training, only two assessed transfer to clinical practice, 33 were uncontrolled, and all were rated at high or critical risk of bias [62]. The obstetric and gynecologic review found no clear benefit of simulation-based ultrasound training over live-model training [58]. The multicenter TEE trial reported improvements in knowledge and practical-test performance but did not evaluate patient benefit [30]; the TEE meta-analysis also reported gains in skills and knowledge, although the certainty of the evidence was low or very low [31]. Current evidence supports the immediate benefits of SBUE for knowledge and task-specific performance, but robust evidence that these gains translate into sustained performance in patient care or better patient-centered outcomes remains scarce.

Current Limitations

Considerable variation exists across SBUE studies in design, learner experience, training dose, assessment methods, outcome definitions, and follow-up duration [49,62,64]. These differences make it difficult to compare or combine findings and to apply them across learner groups and training programs. Consistent reporting of learner characteristics, training dose, simulator fidelity, competency endpoints, and follow-up of clinical transfer would improve comparability across studies.

Evaluation has largely focused on performance during or shortly after simulation training. Whether these gains are retained or transferred to patient care has been examined less often, and patient-centered outcomes are rarely assessed [31,49,62]. This makes it difficult to determine the longer-term clinical effects of SBUE.

Many built-in simulator metrics have not been adequately validated for assessing competence. Studies of FAST, upper abdominal ultrasound, and thyroid ultrasound found that only some built-in metrics could distinguish novices from experts [50-52]. This limits their use in learner-progression decisions and as common measures of competence across training programs.

High-fidelity simulators may require substantial financial investment, limiting access in resource-constrained settings, particularly in low- and middle-income countries. Lower-cost technology-enhanced approaches may still face connectivity, software, and language barriers [43]. Although an international consensus framework identifies the core elements of ultrasound competence [56], curricula and assessment practices remain variable [64], and consistent performance benchmarks for learner progression have not been widely adopted across training programs.

Future Directions

Only 2 of the 42 studies in a systematic review of ultrasound-guided procedure training assessed transfer of procedural skills to clinical practice [62]. A longitudinal training and assessment framework is needed to determine how simulation performance relates to clinical competence. Studies should follow learners from simulation through supervised patient procedures into subsequent clinical practice, incorporating image quality and diagnostic decision-making rather than ending assessment when simulation training finishes. Such studies could directly test which simulation metrics reliably predict image acquisition and diagnostic decisions during patient procedures.

Retention studies need to account for clinical exposure, refresher training, and delayed assessment across tasks and learners [49]. A uniform refresher interval or single threshold for clinical authorization may overlook these differences. In a systematic review of 31 studies involving 1,638 learners, POCUS competence declined during follow-up periods of 1-12 months, most markedly in image acquisition. The decline was greater after courses lasting ≤ 4 h than after longer courses, suggest-

ing that refresher training should reflect the training dose, clinical context, and task [49]. Task risk and demonstrated performance could inform decisions about refresher timing and progression to supervised practice [46,56]. Future programs could include a retention plan with scheduled reassessment and refresher training. Brief courses and high-risk tasks may require earlier reassessment, with refresher training targeted to identified deficits, particularly in image acquisition, and progression based on reassessed performance rather than course completion alone.

Artificial intelligence, virtual and augmented reality, digital platforms, and remote teaching are expanding the ways in which SBUE learners practice and receive feedback. Artificial intelligence may support image-quality guidance and standard-plane recognition, and may eventually support error detection and feedback generation [66,67]. Virtual and augmented reality may support spatial awareness, procedural rehearsal, and hand-eye coordination. Digital platforms can facilitate repeated, self-directed practice, and remote teaching may broaden access to expert guidance [67]. In a small study of military medical students, an app-based POCUS platform did not improve overall FAST performance compared with PowerPoint-based instruction [68]. A meta-analysis of 59 randomized controlled trials found an overall learning benefit from technology-enhanced simulation compared with traditional teaching (effect size, 0.80; 95% confidence interval, 0.60-1.00), although direct evidence on patient and public health outcomes remains limited [69]. Emerging technology-enhanced simulation approaches are promising, but their educational value should be established through empirical evaluation based on defined learning objectives and comparison with relevant training alternatives.

Conclusions

SBUE provides safe, repeated practice before learners work with patients. Its place in a curriculum depends on the clinical task, competency objective, learner experience, and available resources. Feedback and assessment at successive stages should support the move into supervised patient procedures and inform later refresher training. Evidence linking simulation to clinical competence and patient outcomes remains limited. Future assessment frameworks should track that progression into practice and incorporate artificial intelligence, virtual reality, and telesimulation to support the transfer of learned skills.

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Authors' Contributions

Weidan Lu searched the literature and drafted the manuscript. Ruina Zhao contributed to the literature review and manuscript revision. Jibin Liu provided substantive academic guidance. Bo Zhang conceptualized and supervised the review and revised the manuscript. All authors read and approved the final manuscript.

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Data Availability

Data sharing is not applicable to this article as no new datasets were generated or analyzed.

Declarations

Ethics approval and consent to participate

Not applicable.

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Consent for publication

Not applicable.

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