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REVIEW

Central venous catheterization training: current perspectives on the role of simulation

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Abstract: Simulation is a popular and effective training modality in medical education across a variety of domains. Central venous catheterization (CVC) is commonly undertaken by trainees, and carries significant risk for patient harm when carried out incorrectly. Multiple studies have evaluated the efficacy of simulation-based training programs, in comparison with traditional training modalities, on learner and patient outcomes. In this review, we discuss relevant adult learning principles that support simulation-based CVC training, review the literature on simulation-based CVC training, and highlight the use of simulation-based CVC training programs at various institutions.

Keywords: simulation, central venous catheterization, assessment, competency, central line insertion

Introduction

Central venous catheterization (CVC) is one of the most common procedures undertaken in the hospital setting. Over five million central venous catheters are placed yearly in intensive care units (ICUs) in the US.[1–3] A range of medical professionals with a wide spectrum of skill levels carry out CVC and require training. Complication rates vary depending on the site of insertion.[4] The most common complications include central line-associated bloodstream infections (CLABSIs), arterial puncture, hematoma, and cardiac arrhythmia.[5] CLABSI and arterial cannulation have been shown to significantly increase the risk of death.[6] Moreover, pneumothorax and air embolism are well-described complications that occur less frequently but lead to morbidity and mortality.

Multiple medical organizations including the American College of Surgeons (ACS), American Thoracic Society (ATS), American Society of Critical Care Anesthesiologists (ASCCA), Society of Critical Care Medicine (SCCM), Infectious Disease Society of America (IDSA), American College of Chest Physicians (ACCP), and Society for Healthcare Epidemiology of America (SHEA) have published guidelines on central venous catheter insertion. These guidelines include rigorous practitioner educational training and performance evaluations to mitigate complication rates and improve catheterization success.[2,7–9] As the medical community moves away from the "see one, do one, teach one"[10] method of procedural learning to that of deliberate practice,[11] simulation-based training has become a well-recognized tool in medical education for training.

Simulation-based educational initiatives for CVC training improve learner performance and confidence, and have led to improvement in some patient outcomes.[8,9,12–14]

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Simulation is among the most frequently studied educational modes for procedural instruction in invasive bedside procedures.[15]

In this narrative review, we discuss relevant theory from adult learning principles and review the literature evaluating the efficacy of simulation-based training and assessment. We highlight the use of simulation for CVC training at various institutions, and review the literature on assessment tools for simulation-based CVC training.

Traditional training practices vs simulation-based approaches

Historically, supervised practice has been the most common technique to teach CVC. It has a number of benefits – high-fidelity practice, in-the-moment feedback, and cost efficiency. The major limitation to supervised practice is that there is a patient at the other end of the trainee's practicing hand. Simulation-based training for CVC is a way to mitigate the risk to the patient whereas observing and providing specific feedback on a skill that requires improvement which can be practiced over and over again. This is called deliberate practice.

Deliberate practice is a prescriptive educational intervention with nine elements, including motivated learners, a well-defined task(s) and/or objectives, focused repetitive practice, reliable measurements, feedback and error correction, and evaluation and skill advancement.[8,16] Deliberate practice through simulation has been shown to be more effective than "traditional" educational practices for skill acquisition in a number of domains.[8,11] The ability to structure a task and objectives around a repetitive task geared toward a particular skill level in simulation provides a valuable opportunity for learners. For example, a novice trainee may struggle with maintaining sterile technique and holding the ultrasound probe and needle properly whereas a more skilled trainee may have mastered these skills but struggles with keeping his needle point in view on ultrasound when accessing the vessel. Simulation-based training with deliberate practice affords an opportunity to master a particular skill set without forcing a trainee into a situation they may not be prepared for with a real patient.

There is evidence suggesting that more traditional methods of practice, training, and defining competence are lacking. Many institutions rely on the number of procedures conducted as an indication of competence.[17,18] For example, Barsuk et al evaluated the association between procedural experience and performance and found that despite positive associations between self-reported experience and simulated procedure performance, overall performance in CVC based on a validated checklist assessment was poor.[19] Central line proficiency after simulation training was shown to improve trainee performance based on these validated metrics, even in residents with sufficient procedural experience to have been previously deemed competent.[20] Even seasoned practitioners have been shown to frequently miss key elements of proper CVC. In a 2016 study of attending physician-placed central venous catheters, fewer than 50% of attendings studied participated in a timeout procedure, cleaned the area of the central line properly with chlorhexidine, or maintained sterile technique.[21] These studies argue for improved training practices and/or ongoing evaluation of procedural competence in practitioners of all levels, regardless of their self-reported experience.

Learner and patient outcomes using simulation for CVC training

Studies evaluating the efficacy of specific simulation-based training curricula for CVC are heterogeneous with varying learner levels, varying types of simulators, variable supplementary teaching modalities, non-standardized assessment tools, and lack of consensus on determination of competence. The largest systematic review and meta-analysis by Ma et al[22] evaluated 20 quality[23] research studies that described simulation-based educational interventions taught to learners of various levels. Notably, only three of these studies are randomized controlled trials.[24–26] All of the studies used either commercially available mannequins, homemade trainers, animal models, computer software, or virtual reality programs. The studies all included a control group that had not received a simulation-based training intervention. Outcomes of this meta-analysis and more recent studies focus on: 1) learner performance, 2) learner attitudes, and 3) patient outcomes. The use of simulation-based training has demonstrated improvements in all three categories.

Learner performance and skill retention outcomes

Due to a lack of standardized assessment modalities, reports of learner performance outcomes are variable. The majority of studies report improvements in learner performance as assessed on simulators rather than real patients. Various assessment modalities were used with differing degrees of reported validity and interrater reliability, but included checklist assessment, global rating scales, knowledge assessments, and number of needle passes.[22] Some studies have shown improved learner performance as it pertains specifically to portions of the procedure such as ultrasound use[13] or use of sterile technique.[27,28] In a randomized-controlled trial of 52 interns, those who were simulation-trained demonstrated better adherence to prescribed procedural technique than did traditionally trained interns who received a didactic lecture, online module with video, had time dedicated to familiarization with the checklist, and supervised practice.[24] Similar improvements to protocol adherence after simulation-based education have been replicated.[27] Recent studies have used first needle pass success and failed needle pass attempts as a "pass/fail" modality and have shown improvement in this endpoint after simulation-based ultrasound-guided CVC.[29]

Depending upon the timing of intervention and assessment, comparisons of performance pre- and post-intervention may not reflect either true skill retention or transfer of skills to clinical encounters. Few studies have examined skill retention rates acquired from simulation-based education interventions versus traditional procedural training. One study found skill improvements persisted with delayed testing 3–4 weeks after a simulation-based intervention using chicken meat.[30]

Learner attitude and knowledge outcomes

Improvements in learner confidence, satisfaction, and knowledge after simulation-based CVC training are well documented. These outcomes are collected via self-reported Likert scales and pre- versus post-intervention questionnaires and tests.[9,13,22,25,28,31–36]

Patient clinical outcomes

Correlating patient clinical outcomes with educational interventions is difficult, given the relatively low number of adverse events and typically smaller study sizes in medical education research studies. The most commonly reported patient-oriented clinical outcome is the number of needle passes, which has been used as a surrogate for risk of hematoma, arterial puncture/injury, and pneumothorax; several studies have shown a decrease in the number of needle passes after trainees completed simulation-based educational interventions. Included in the meta-analysis previously described was a large study of 76 residents who completed a simulation-based training program and were required to pass a validated assessment checklist prior to undertaking the procedure on patients. This study found that simulation-trained residents reported fewer needle passes, arterial punctures, catheter adjustments, and higher success rates than traditionally trained residents. This simulation-based mastery learning program increased residents' skills in simulated central venous catheter insertion and decreased complications related to insertion.[13] In aggregate, arterial puncture risk remained stable before and after implementation of simulation training curricula.[22,36]

The effects of simulation-based interventions on the rates of CLABSI are less telling. Ma et al pooled three studies and showed that simulation training was not associated with significant differences in catheter-related infection risk.[22] However, a more recent study in community-based medical ICUs evaluated the rate of CLABSI after the introduction of a simulation-based mastery learning intervention and found a decrease in CLABSI at a rate of 3.82 per 1,000 catheter-days pre-intervention versus 1.29 infections per 1,000 catheter-days after the intervention, boasting a 74% reduction in the incidence of CLABSI in the medical ICUs with their simulation education intervention.[12]

In summarizing the data on learner and patient outcomes after simulation-based CVC training programs, there is strong evidence to suggest improvement in learner outcomes in comparison to more traditional training methods. There is a decrease in patient adverse events related to CVC if the trainee has undergone a simulation-based training program. A limitation in grouping the outcomes of these studies is that they are heterogeneous in regard to learner levels, types of simulation-based interventions, and comparative "traditional" training curricula. Another potential limit is the time-on-task effect,[37] which describes potential bias toward an intervention as a result of more learning time spent during that intervention when compared to the alternative. Time spent on CVC training was variably reported in these studies and was not compared to time spent training on non-simulation-based modalities for comparison.

Variations of simulation-based central venous catheter training

Types of simulators

A variety of simulation trainers are used for CVC training (Table 1). Most studies comparing simulation-based CVC training curricula involve the use of commercial mannequins as task trainers. A wide variety of commercial mannequins are available, ranging from $700–$3,000, depending on various features of the models. Variable features include ultrasound capabilities, skin durability, and pump function, to name a few. Task trainers are available for internal jugular venous catheter placement, subclavian venous catheter placement, and femoral venous catheter placement.

Alternatives to commercial mannequins exist, and have been studied. Human cadavers have been used for

Table 1 Advantages and disadvantages of various types of simulators for central venous catheterization

Types of simulators	Advantages	Disadvantages
Mannequin	• High-fidelity models available • Ultrasound-compatible • Easily adaptable to hybrid simulation	• Cost (unless homemade) • High fidelity not guaranteed based on type of model • Often, cannot dilate or cut without permanent damage to the model
Non-human tissue	• Inexpensive • Ultrasound-compatible • Reported high fidelity compared to some commercial mannequins	• Potential bacteria exposure from raw meat in non-human tissue
Cadaveric tissue	• High fidelity • Potentially ultrasound-compatible	• Scarce resource
Virtual reality	• Precise feedback • Easily accessible to trainees for practice	• Lower fidelity • Ultrasound capability limited

simulation-based CVC training with reports of high fidelity.[38] Simulation training on non-human tissue, such as chicken breast, has been used.[30,39] One study found that a chicken model simulator was rated more highly in regard to ultrasound quality and tissue feel in direct comparison with a commercial mannequin.[39]

Homemade CVC simulators have been evaluated and have shown promise. For example, a homemade simulator made from silicone, tubing, and a pressurized pump system was found to be more highly ranked in quality as compared to three alternative commercial models.[40]

Several computer-based and virtual reality-based tools have been studied. Focused practice and fine-motor skill evaluation with virtual reality-based simulators have been shown to improve needle insertion time, idle time, and hand smoothness during repeated simulated subclavian line insertions.[41] Moreover, robot trainers are in development to provide practice and personalized feedback.[42] In other procedural training, virtual reality has been used to develop and assess trainee skills by measuring surgical tool motion and psychomotor skills.[43,44]

Variations in simulation-based training techniques

In addition to variable equipment, various simulation-based techniques for training in CVC insertion have been described. We focus on hybrid simulation and error-focused simulation techniques that have been studied.

Hybrid simulation is defined as the "use of two or more simulation modalities in the same simulation activity."[45] This method has been effective for improving medical student confidence in a variety of procedural skills.[46] Examples of hybrid simulation scenarios often involve a mix of mannequin and confederate participant or standardized patient. Learning objectives can be added either in sequence or in parallel to add difficulty or expand the amount of content delivered. For example, a learner who is accomplished at the steps of CVC insertion might be challenged by the addition of a disruptive family member or a simultaneous complication that they now must manage. Hybrid simulation scenarios may allow for larger groups to be engaged during a single scenario, which is another added benefit.

Using errors as an educational tool has become increasingly recognized as a critical component of procedural training, and one that is often neglected.[47–49] Error-exposure training is an educational approach that encourages exposure to errors during initial skill acquisition to promote error identification and management. Error-exposure training can lead to error avoidance and higher trainee performance.[50] A study of a simulation-based CVC insertion training program for surgical interns with incorporated error-based activities and discussion shows that learners had better retention of CVC skills 1 month after the session, as compared to surgical interns who did not receive error-exposure training. The intervention in this study included feedback discussion framing errors rather than feedback focused on carrying out correct steps. Quoting from the study, one might say "now think about what would happen as a result of that error and how you would manage it."[51]

Simulation to assess procedural competence

There is no gold-standard assessment method to assess for CVC competence. Many simulation-based programs described in the literature combine both formative and summative components of their program that occur within a single isolated session. Experts and authors have used varying markers of competence, including but not limited to: the number of needle passes, completion of the procedure without assistance or complication, post-training knowledge tests, hand-motion analysis, and successful completion of a CVC insertion checklist. Different assessment modalities come with a variety of advantages and limitations (Table 2).

Table 2 Advantages and limitations of assessment modalities validated for simulation-based central venous catheterization training

Assessment modality	Advantages	Limitations
Checklist	• Objective • Allows for domain-specific objectives • Good interrater reliability	• Frequently lacking in patient-centered domains such as communication or safety
Global rating scale	• Allows for domain-specific objectives • Superior validity to checklist	• Inferior interrater reliability to checklist • Less objective
First-attempt pass/fail	• Objective	• Narrow-domain assessment focus • Possible to pass by luck
Hand-motion analysis	• Provides highly specific feedback for improvement	• Narrow-domain assessment focus

The most common approaches are checklists, global rating scales, or a combination of the two.[52] Checklists are often favored in the assessment of technical skills as they consist of objective observable behaviors that are either present or absent. Similarly, global rating scales grade performance on a Likert scale, which is based on an overall impression of performance on a particular procedure item. The global rating scale has demonstrated higher internal reliability and lower interrater reliability than checklist assessment, although checklist scores for procedural competence also demonstrated acceptable discrimination for a variety of bedside procedures.[52] A study from 2014 evaluated existing published tools measuring competence in CVC and found 25 studies that assessed a total of 147 performance items.[53] Twelve of the 25 studies involved assessment during simulation (rather than in a real clinical scenario). All studies in this review analysis utilized a checklist.[9,13,36,54–61] Approximately one quarter of the studies used a global rating scale.[9,58–60,62,63] The checklist item themes are well-analyzed by Ma et al; they noted that, in checklists involving simulators, there was a greater representation of items in the domain of "procedural competence" and that the domains of "team work" and "communication and working with the patient" were under-represented.

The validity and reliability of assessment tools are variably reported. Of the 12 studies utilizing simulation for evaluation, seven described their procedure for content validation[13,30,36,56–59] and 10 reported interrater reliability.[9,30,36,56–61]

Hand motion, as analyzed by sensors and computers or expert observation, has been employed as a means of assessing mastery of ultrasound-guided CVC during simulation.[64–66] The Imperial College Surgical Assessment Device (ICSAD) is a motion-tracking device that has been validated as an assessment tool for ultrasound-guided CVC.[65,67] ICSAD sensors are placed on the back of the trainee's hands under their gloves and several parameters are recorded, including duration of the procedure, number of movements, and traveled path length of each hand. To establish the ICSAD construct validity, Corvetto et al evaluated the ability of the ICSAD to discriminate technical proficiency and found it was able to distinguish between novices, intermediate-level operators, and experts.[65]

Translation into practice and highlights of institutional experiences

Curriculum design

In the vast majority of simulation-based training programs reported in the literature, simulation was combined with additional training, such as didactic sessions and educational training videos. One group demonstrated success with a mixed-methods training curriculum that included simulation on mannequins followed by a problem-based learning session to focus on recognition and management of CVC complications; resident trainees reported preference for this mixed-methods curriculum.[68] Frequently described in curriculum design is division of the various components of the central line insertion procedure into different skill acquisition steps (e.g. vascular anatomy and landmarks, informed consent, sterile technique, ultrasound usage, and kit familiarization). A majority of simulation-based curricula include a component of didactic teaching.[22]

The Mayo Clinic Method described a program whereby interns participated in a simulation-based ultrasound training module during their internship that utilized didactic and practical experiences in a simulation and cadaver laboratory. This program was standardized across three institutions.[69] The basis of this mixed methodology, simulation-based training program was further modified and reported in a recent study by Alsaad et al. Their curriculum was divided into four training sections: 1) a 30-minute review of anatomy at the various insertion sites, 2) a 30-minute review of sterile technique and universal precautions, 3) a 45-minute training session on ultrasound use, and 4) a 45-minute hands-on practical station with task trainers while using a CVC insertion checklist. Trainees underwent proficiency assessment by an instructor wherein they received no instruction and were required to conduct 11 predetermined critical actions on the checklist. If one of these critical actions was not completed, the trainee was required to repeat the simulation training component and the proficiency assessment.[20]

While most studies focus on resident trainees, hospital-wide initiatives have also been reported.[12,70] Grudziak et al demonstrated improved knowledge and confidence levels in a hospital-wide simulation program that included 1) an ultrasound session, 2) kit familiarization and sterile technique station, 3) demonstration of central line insertion on a trainer, and 4) trainee placement of ultrasound-guided internal jugular central line.[70]

Appropriate timing of simulation-based CVC training and consideration of skill atrophy

Time is a precious resource for trainees in the medical field, and there are multiple competing interests when it comes to medical education curricula. The optimal time for trainees to undergo simulation-based CVC training is unknown. It is not clear how long trainees retain the skills they learn after simulation-based training for CVC. The commonly used Mayo Clinic Method was implemented during the orientation program for interns. Other studies have demonstrated success with implementation of central line simulation just before, or during, the ICU experience.[62] No studies have been undertaken to compare the timing of central line simulation as it relates to trainee performance or skill retention.

Skill atrophy has been shown to occur over time after procedural training. Several studies evaluated for "skill atrophy" in simulation-based training programs were compared with the traditional procedural training and it was found that, in both groups, there was generally some decline in performance after a certain amount of time. The improvement seen in procedural skills with a CVC insertion simulation course has been shown to decay such that it offered no long-term benefit over traditional methods of procedural teaching.[71] The timing of skill decay is variable in the current literature. A single study showed skill decay 3 months after a simulation-based intervention;[72] another reported at least a 1-year retention of central venous catheter insertion skills after simulation-based mastery learning (trainees were assessed at 6 and 12 months). The authors and experts include the caveat that individual performance is variable and, therefore, periodic testing and refresher training is recommended.[73] Residents who are off of clinical rotations report significant skill atrophy, which may support a more longitudinal curriculum.[74]

Perceived barriers to using simulation for central line insertion training

As the evidence mounts in favor of simulation-based CVC training, programs across a variety of specialties and training levels have adopted the practice. The major barriers perceived by institutions may involve resources such as cost, faculty support, time, and space. A less likely barrier is the now-rarely cited criticism that simulation-based training for CVC is low-fidelity and, therefore, low yield – there are plentiful data to negate that criticism.

The consideration of financial resources for simulation-based training programs can be daunting when the cost for operation of simulation centers is considered.[75,76] More recent data looking at potential cost-savings associated with a simulation-based CVC training program provides backing for investment.[28,77] Cohen et al converted the number of prevented CLABSIs in the year after their simulation-based CVC training program into dollars saved and found a net annual savings of greater than $700,000 (accounting for 10 prevented CLABSIs and their associated increase in number of hospital days). This was from an investment of $112,000 into their simulation-based program.[77]

The task trainers frequently used for CVC training are generally technologically simple and, therefore, user-friendly and require little preparatory training. Suggestions for incorporating a simulation-based CVC training program in a time- and space-limited setting might include using a single task trainer in a conference room (with a faculty member and an ultrasound) during a noon conference or morning lecture period. Supportive online modules and videos[78] can help to prepare learners prior to their simulation session. These videos can either be made locally by the institution, or already created tools from MedEdPORTAL or YouTube can be utilized.

Future direction

Whereas the data are compelling for simulation-based CVC training, the variation of practice and methods studied leaves some questions about optimal curriculum design. Currently, there is a paucity of data on the comparison of various simulation curricula. Further investigation will help to elucidate which components of mixed-methodology training programs complement simulation to maximize learner and patient benefit. Furthermore, studies on appropriate timing of simulation-based interventions for trainees are lacking and are a potential area of future investigation.

Conclusion

The shifting paradigm of medical education to promote thoughtful strategies that complement the way adults learn is reflected in the enthusiasm for simulation-based procedural education. Several studies have highlighted the benefits of simulation on learner and patient outcomes and have even proven it to be cost-effective when adverse events are avoided. Intrinsic in the success of a simulation-based training program is the ability to monitor trainee progress in skill acquisition and transfer to real patient care. The literature offers several well-validated tools for assessing trainees' skills in carrying out CVC during simulation. Encouraging data exist to suggest that requiring trainees to exhibit a level of "mastery" of the procedure in a simulated session can decrease patient harm. Although evidence seems overwhelmingly in favor of the inclusion of simulation-based education methods for CVC training, more investigation is needed to determine the optimal delivery of this novel training modality. When and how often should simulation-based training and/or evaluation occur and what specific simulation-based curricular elements are highest yield for adult learners? These are questions that remain unanswered.

Disclosure

The authors report no conflicts of interest in this work.

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