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Use of a Novel Three-Dimensional Model to Teach Ultrasound-guided Subclavian Vein Cannulation

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ABSTRACT

Background: Central venous cannulation is an essential skill in perioperative and critical care medicine. Ultrasound guidance is the standard of care for femoral and internal jugular vein access, with the subclavian vein being perceived to be less amenable to ultrasound-guided (UG) insertion, resulting in a lack of procedural competency and low cannulation rate. There is a paucity of resources and a lack of experience among staff physicians to effectively instruct trainees. Simulation-based medical education has the potential to help maintain high-stakes, infrequently performed skills and counteract possible unrecognized skill decline. We aimed to create a novel, low-cost,

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high-fidelity three-dimensional (3D) model for UG subclavian vein (UG-SCV) access with an accompanying curriculum to improve this important skill.

Methods: A curriculum was created consisting of preparatory material reviewing UG-SCV access, followed by an in-person didactic lecture focusing on ultrasound use and management of complications and a deliberate practice session scanning volunteers and practicing UG vascular puncture on a 3D model. A qualitative usability test design was used to assess the validity of the curriculum in trainees with advanced vascular access skills (anesthesiologists). Participants were second-year anesthesia residents, anesthesia fellows, and staff physicians. Focus groups conducted after each session explored the face validity of the model and curriculum. By applying a usability design, the curriculum was optimized and finalized.

Results: Between September 2020 and February 2021, 28 participants tested the curriculum. The focus groups ensured that the curriculum achieved its objective, with iterative changes made after each session in a quality improvement framework Plan-Do-Study-Act approach. After the third cycle, minimal changes were suggested, and the curriculum and 3D model were finalized. An additional group of participants was used to ensure that no new input would help improve the curriculum further.

Conclusions: A focused curriculum for enhancing skills in UG-SCV cannulation using a novel 3D model was successfully implemented and validated through a usability test design. This curriculum is better targeted for practitioners experienced in central venous access to master a subclavian approach and maintain their skill level.

Keywords:
education; central venous access; simulation; point-of-care ultrasound

Successfully establishing central venous cannulation (CVC) is critical in perioperative, emergency, and critical care medicine. Ultrasound guidance (UG) is the standard of care for internal jugular vein and femoral vein cannulation in North America. In the past, subclavian vein (SCV) cannulation has been described as a more complex and technically difficult skill that is less amenable to UG. With growing experience in point-of-care ultrasound, UG-SCV cannulation will almost certainly become the standard of care (1). The rate of complications from SCV cannulation in the literature is high (21%) (2). The complications can be devastating and include phrenic nerve injury, hematoma, hemorrhage, pneumothorax, line infection, tamponade, and death (3, 4). It is easy to appreciate why this procedure is performed less frequently and is even more infrequently taught (3, 5). Nevertheless, SCV cannulation remains an important yet degrading skill. Advantages of SCV include patients with raised intracranial pressure or significant hypovolemia (3), and, in some cases, the SCV is the only accessible site. There are data to support the SCV as having a decreased risk of infection and thrombosis (5). UG-SCV cannulation may improve the success rate and reduce complications and failed catheterizations compared with landmark-guided techniques (3, 6). Unfortunately, there is a paucity of studies specific to UG-SCV cannulation (6).

Simulation is a valuable method for learners to acquire and rehearse complex technical skills without exposing patients to risk (7), but it is costly (8–10). It lets learners practice frequently, allows them to build a mental representation of a procedure, and increases their visuospatial skills and confidence. CVC-experienced physicians rated the complexity and technical difficulty of UG-SCV cannulation as very high (8/10) (3). As technical proficiency with a skill declines, so too does the ability to teach that skill (3, 5). The self-confidence of practitioners does not correlate with proficiency, contributing to adverse outcomes (9).

Davis and colleagues (11) have demonstrated a simulation training program for UG-SCV cannulation that enabled participants to successfully insert a CVC. This study was limited, however, because it did not formally assess the curriculum, and the simulation used a lower-fidelity phantom, which limited the understanding and execution of UG-SCV cannulation. The aim of our study was to assess the quality and face validity of a newly developed UG-SCV curriculum using a novel, inexpensive three-dimensional (3D) model.

METHODS

Curriculum Creation

A prestudy needs assessment was completed by 14 staff anesthesiologists, 4 of whom had used UG-SCV cannulation. Numeric rating scales demonstrated a 9/10 comfort with other CVCs but only 4/10 comfort with SCV cannulation, as well as a 9/10 rating for interest in learning UG-SCV. The simulation curriculum maximized acquisition of knowledge and skills necessary for successful UG-SVC and consisted of three parts: a review of preparatory materials, a didactic lecture, and deliberate practice using the 3D model and volunteers. The components were similar to other educational design models in the literature (2, 5, 10–12). The preparatory materials were selected by the primary investigator (S.P.).

Learners were trusted to complete the required precourse work. Participants were asked in an e-mail before the session to review the *New England Journal of Medicine* video titled *Ultrasound-guided Cannulation of the Subclavian Vein* (13) concurrently with a handout (*see* Appendix E2 in the data supplement) to create a mental foundational framework for this task. Supplemental online websites were suggested for participants to review as required (*see* Appendix E3). An informal poll was performed to judge participants' commitment to learning.

The 45-minute-long mandatory in-person didactic lecture was created and delivered by authors with experience in UG vascular access directly before the deliberate practice. It was modified iteratively with focus group feedback. The deliberate practice component lasted 45 minutes, during which participants acquired ultrasound images of humans. A novel 3D-SCV model was used concurrently to practice in-plane and out-of-plane UG needling (unlimited attempts). The teacher-to-learner ratio was 1:4 (14). *See* Multimedia Appendix E1 for a video of simulated cannulation on the 3D model. Participants used the Central Line Insertion Standard Work and Safety (Bundle) Checklist for OR. This peer-reviewed expert opinion checklist was added to the curriculum as the competency evaluation of procedure execution (1). Finally, participants were given 15 minutes to complete a postcurriculum conceptual and knowledge test (*see* Appendix E4) for formative purposes with the explicitly stated goal to review and reflect on the provided material and training. This test was created using a Delphi method, including experts to ensure that content and quality were accurate and relevant, and iteratively changed on the basis of focus group feedback. Fifteen minutes were then allowed for questions, wrap-up, and course evaluation.

Model Creation

The high-fidelity 3D model includes the SCV and artery with additional landmarking structures (lung, clavicle, manubrium of the sternum, first rib), and is manufactured using material conducive to ultrasound scanning (Figure 1). The prototype costs $3,500 CAD; subsequent models cost $800–$1,100 CAD (manufacturing/assembling process; *see* Appendix E1).

Study Design

To assess the quality and face validity of the curriculum, a usability test design was used. The study was conducted at a tertiary academic hospital in Toronto, Canada. The curriculum was open to all resident physicians (Postgraduate Year 2 or above), clinical fellows, and staff anesthesiologists in the Department of Anesthesiology and Pain Medicine. After the initial design, three test development cycles with a minimum of 24 participants (homogeneous group, one specialty) were planned, with a final test-only cycle. The initial session was launched with novice learners to determine if training novices in the more advanced UG-SCV access would be feasible and useful. Subsequent sessions were developed on the basis of feedback from each usability test cycle. Each test cycle included a focus group to obtain qualitative data to inform iterative changes. Modifications were based on focus group feedback and addressed identified gaps and learning needs. Learning objectives and educational strategies were established and iteratively modified on the basis of feedback using Bloom's taxonomy

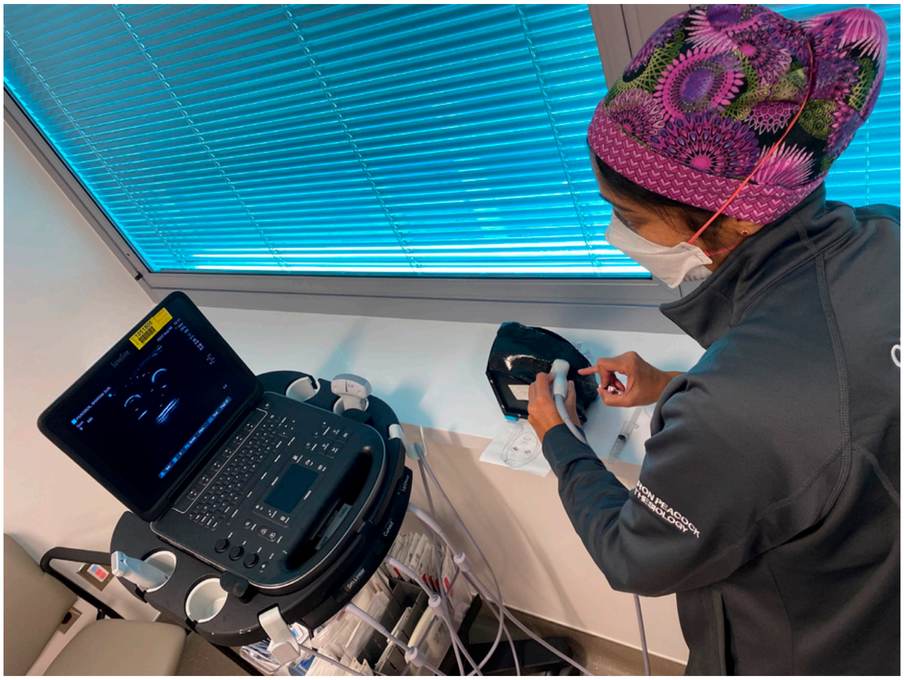

Figure 1. Setup of the three-dimensional printed model of subclavian vein and artery.

and focus group feedback. Additional test cycles would have been added if saturation had not been reached.

Measures

Process measures included time to complete didactic and deliberate practice sessions and time to complete knowledge tests. Balance measures included the number of students in each session and the experience level of participants. Outcome measures were utility of the 3D model and face validity of the final UG-SCV curriculum.

Intervention

After local research ethics board approval, participants consented to complete the curriculum. Figure 2 summarizes the process. Focus groups were conducted at the end of each session. The feedback was used to modify the curriculum and/or 3D model for subsequent sessions.

RESULTS

The study was performed between September 2020 and February 2021, with a total of 28 participants completing the course (16 residents, 6 fellows, 6 consultants). The focus groups were conducted by a study author not involved in the design of the curriculum following an interview guide. Feedback was anonymized for curriculum creators. Anonymized transcripts were used for coding purposes. Feedback was

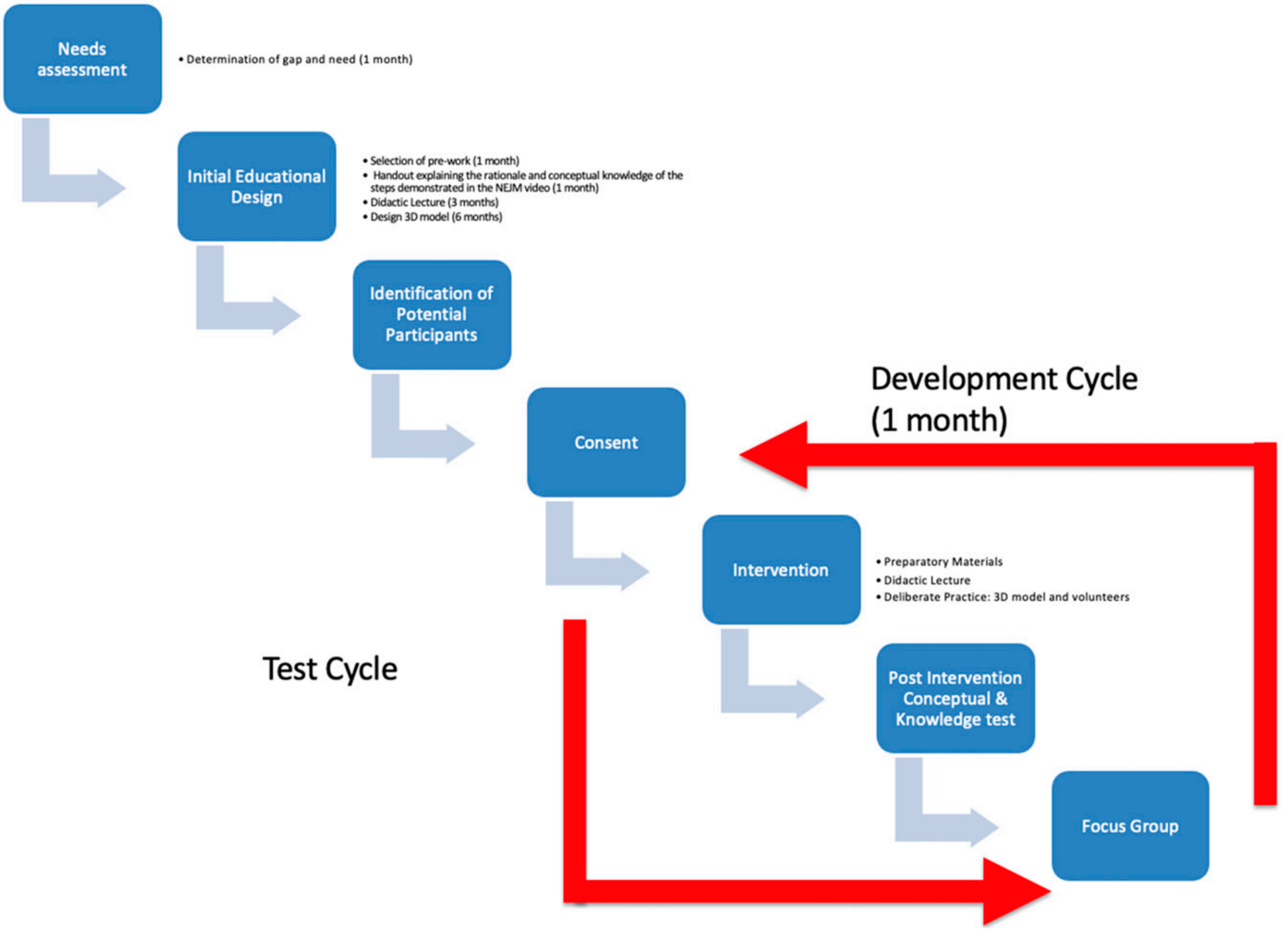

Figure 2. Summary of the educational process.

Table 1. Usability test cycle Plan-Do-Study-Act chart

	Session 1	Session 2	Session 3	Session 4
Plan	Development of didactic material and 3D model	Curriculum modification	Refinement of curriculum	Finalize curriculum
Do	Pilot study with novice learners (anesthesia residents)	Advanced anesthesia clinicians (anesthesia clinical fellows and consultants)	Usability test cycle with advanced anesthesia clinicians	Usability test cycle with advanced anesthesia clinicians
Study	Ambiguity in ideal learner/level of experience Quality of curriculum Fidelity of 3D model Quantity of material Transferability of skills	Fidelity of 3D model Level of instruction and direction with deliberate practice	Efficiency and efficacy of curriculum Level of experience	Efficiency of curriculum delivery
Act	Didactic material Required more basic concepts 3D model Model was too advanced; simpler model would be better for ultrasound needle guidance skills Changes to improve the usability (i.e., suction cups to stabilize on table) Deliberate practice Increase familiarity with central venous catheter kit and with Seldinger technique Smaller group sizes for deliberate practice with a consistent teacher/learner ratio Level of experience Novices felt PGY 4 and 5 would be experts in UG-SCV cannulation	Didactic material Made a separate advanced presentation removing foundational concepts on central venous access Created a preparatory presentation and included foundational concepts removed from presentation More focus on identification and management of complications 3D model Changed size and depth of vessels, changing contour of thorax, add a clavicle Deliberate practice Be explicit to practice on different group members to see anatomical differences Test Did not consolidate or improve knowledge Level of experience PGY 4–5 and beyond or ICU fellows	3D model Label and orient model re: cephalic/caudal/lateral/medial Deliberate practice Maximize practice time Be explicit to practice on different group members Level of experience Fellows and staff	Test Uncertain of utility

Definition of abbreviations: 3D = three-dimensional; ICU = intensive care unit; PGY = post-graduate year; UG-SCV = ultrasound-guided subclavian vein.

independently reviewed by two experts to ensure consistency in identifying themes, and subsequent curriculum changes were made by consensus. Consensus was achieved by the final test cycle as planned. The only additional suggestion for improvement was to consider reducing the number of posttest questions.

Based on the feedback, the curriculum was deemed most appropriate for experts in CVC who had little to no experience with UG-SCV cannulation, which is consistent with other studies (6, 11). The Plan-Do-Study-Act cycles are detailed in Table 1. Educational themes identified were translation to clinical practice (skill acquisition to practice, ultrasound skills, clinical applicability, direct supervision, developing clinical competence, transferable skills), satisfaction with curriculum components and design (video, troubleshooting and complication management, deliberate practice, feedback), level of expertise, anatomical model, examination and competency.

DISCUSSION

This study is the first to develop, evaluate, and disseminate a robust and inexpensive curriculum specific to the SCV using low-resource and cost-effective simulation tools outside of a simulation center. This reproducible simulation curriculum for UG-SCV cannulation provides the framework to produce a 3D model, which is a novelty of this study. Multiple groups of anesthesia trainees, experienced fellows, and consultants completed the curriculum, demonstrating usability and confirming face validity. Consensus for the final curriculum was reached.

Simulation training for CVC is typically performed with commercial task trainers or high-fidelity mannequins, with costs ranging from $1,000 to $8,000 USD (15). Other researchers have developed a low-cost reusable model for UG-SCV cannulation using gelatin and finger millet flour. They concluded this low-fidelity model was helpful for the development of hand–eye coordination and for improving confidence in SCV cannulation skills (16). A different research group developed a homemade CVC model. Experienced physicians ranked this model superior to three commercial CVC models. The cost of this model was $400 USD (15). Therefore, noncommercial simulators can match or exceed commercial simulators at a fraction of their cost when used by experienced practitioners. Our 3D model recreates the anatomical complexity around the SCV with a clavicle, two vessels, and an open air cavity representing the lung. It can be used multiple times and is resistant to needle tract formation. The inexpensive and easy-to-construct 3D model increases simulation fidelity and makes it more accessible and economically feasible for hospitals to offer frequent training opportunities.

Our simulation curriculum has components similar to those in other curricula on SCV central venous access, which include didactic teaching followed by hands-on training either on task trainers or anatomical models (2, 5, 10–12). These other curricula focused on skill acquisition through deliberate practice supervised by practitioners experienced in SCV access to rapidly consolidate knowledge from the didactic modules. Our curriculum also incorporated all components of an evidence-based consensus on the insertion of central venous access, including minimal training requirements (17).

We provide access to a uniform and consistent training curriculum, which closes educational gaps in an infrequent but important skill to improve the attitude and skill of providers (18). It complements the publication by Davis and colleagues (11) demonstrating a training program for UG-SCV placement that increased performance in simulation. In addition, we provide a critically reviewed curriculum and its components to deliver the most cost-effective means of training. It allows training and assessment of knowledge, skills, and competency of UG-SVC cannulation without involving patients. The preparatory work included the “whys” of the procedure, with the purpose of instructional design to facilitate cognitive integration and retention on procedural skill transfer (19). Competency is more relevant than the number of performances when looking at UG skills (20). The current literature supports UG-SCV cannulation to increase the success rate and reduce complications (6).

Our curriculum was validated through a usability test design, with follow-up focus groups after sessions, where our final cycle demonstrated no further suggestions for change. The major limitation of our study is the single-center design, with input only from anesthesiologists. However, it has since been used successfully to teach intensive care physicians and participants at other institutions. The model did not achieve realistic recreation of the vessels. There was a decreased ability to detect puncture of the posterior wall of the SCV, given the relatively small volume of fluid in the 3D model's vessels. The model, however, allowed air aspiration if the participant advanced the needle into the lung space. Finally, mastery in simulation does not equate to mastery in clinical practice, which remains a limitation of simulation training. Simulation-based training, however, is widely accepted to be safer and superior to traditional apprenticeship methods of acquiring new skills and/or procedures, although there may be no differences in the long term (7, 21). The value of accessible, frequent simulation is to prevent the degradation of skills that are used infrequently in clinical practice, such as SCV access. The major strength of this article is the detailed process of designing and implementing a UG-SCV cannulation curriculum and creation of 3D models for this purpose, which we are making globally available. Further research is required to quantify the benefit of frequent simulation training over on-the-job training and to assess the translation into practice and retention of these skills in actual patients.

CONCLUSIONS

We successfully created and validated a focused curriculum for enhancing skills in UG-SCV cannulation using a novel 3D model. A follow-up study should assess the translation to practice of this curriculum and its capability to enhance patient care and safety. We are making this high-fidelity model and the accompanying curriculum available free of charge as our contribution to making simulation-based training more easily accessible.

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