Explor-A-Thora: A Novel Three-Dimensionally Printed Pleural Simulator

Ilana Roberts Krumm[1], Scott Drapeau[3], Bryan Kim[2], Yaron B. Gesthalter[1], and Lekshmi Santhosh[1,2]

[1]Division of Pulmonary, Critical Care, Allergy, and Sleep Medicine, [2]Department of Medicine, and [3]Makers Lab, University of California, San Francisco, San Francisco, California

ORCID IDs: 0000-0002-3946-8044 (I.R.K.); 0000-0002-9897-3462 (L.S.)

ABSTRACT

Background: For procedural education, the shift from the traditional apprenticeship model to simulation-based mastery has become increasingly accepted as the gold standard and has underscored the importance of high-fidelity, cost-effective training options. However, cost-effective pleural procedure simulators providing both realistic haptic feedback and ultrasound compatibility are lacking.

Objective: We aimed to create a pleural procedure simulator with characteristics of human tissue, at low cost and with ultrasound compatibility.

Methods: This work used design-based research principles and a collaborative rapid iteration approach in collaboration with the University of California, San Francisco, Makers Lab and design-based researchers at the University of California, Berkeley, which led to the creation of a three-dimensionally printed pleural procedure simulator.

Results: The needs assessment indicated significant discomfort with pleural procedures and a request for more accessible simulation opportunities. Iterative prototyping

(Received in original form February 14, 2024; accepted in final form May 1, 2024)

Supported by the University of California, San Francisco, Makers Lab; the University of California Nina Ireland Program for Lung Health Innovations Grant; and the UCSF Innovations in Education Award.

Author Contributions: I.R.K. had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis, including and especially any adverse effects. I.R.K., S.D., B.K., Y.B.G., and L.S. contributed substantially to study design, data analysis and interpretation, and writing of the manuscript.

Correspondence and requests for reprints should be addressed to Ilana Roberts Krumm, M.D., Division of Pulmonary, Critical Care, Allergy, and Sleep Medicine, Department of Medicine, University of California, San Francisco, 505 Parnassus Avenue, Box 0111, San Francisco, CA 94143. E-mail: ilana.krumm@ucsf.edu.

This article has a data supplement, which is accessible at the Supplements tab.

ATS Scholar Vol 5, Iss 3, pp 451–459, 2024

DOI: 10.34197/ats-scholar.2024-0008IN

resulted in a three-dimensionally printed rib cage and a series of innovations in the fluid pocket and skin layers to provide realistic tactile feedback and ultrasound imaging compatibility. The final model costs significantly less than commercial simulators, with durable components and replaceable parts that can be reused multiple times.

Conclusion: The development of a low-cost, high-fidelity pleural procedure simulator addresses the current limitations of commercially available pleural simulators. By integrating three-dimensional printing technology and easily accessible materials, we were able to produce a simulator that closely replicates the feel of human tissue, allows ultrasound use, and is adaptable for different patient anatomies and clinical scenarios. This novel simulator is a scalable solution to elevate the standard of procedural education and ultimately positively affect patient care.

Keywords:
education; simulation; pleural disease

The traditional apprenticeship model of medical education has shifted to a graduated autonomy approach with a focus on simulation-based mastery and maintenance, now considered the gold standard for procedural education (1, 2). Simulation is increasingly recognized as an essential component of developing procedural competence, offering hands-on practice in a minimal-risk environment with large improvements in knowledge, skills, behaviors, and patient-related outcomes (3–5).

In thoracentesis, simulation-based mastery has been shown to improve skill transferability and clinical outcomes (6, 7), but despite this, thoracentesis has been repeatedly identified as the procedure internal medicine (IM) residents are most uncomfortable with, surpassing even central lines and lumbar punctures (8, 9).Thoracentesis, and more advanced pleural procedures, requires the correct identification and interpretation of tactile input to make adjustments and troubleshoot complications, but simulators to facilitate this learning are extremely costly. Despite the high cost of commercial pleural models, learners often perceive them to not be as realistic as human tissue, compounding the difficulty of learning a procedure with which trainees are already uncomfortable. There are multiple commercially available simulation options for pleural procedures, which differ by realism, tactility, haptics, cost, and availability. The simplest task trainers range from $2,500 to $4,000, while ultrasound compatible trainers can cost upward of $6,000, without accounting for replacement parts (https://www.gtsimulators.com).

There are relatively few alternative task trainers available. Some institutions use cadaver-based simulation for more advanced pleural procedures, such as medical thoracoscopy, but these sessions are costly, not amenable to just-in-time training, and impractical for thoracentesis or chest tube simulation. Others use a rack of pork ribs for pleural simulation (10), which again is not suitable for just-in-time implementation and has durability and storage limitations. Even at international conferences, the ability to have high-fidelity pleural task trainers is limited. There have been reports of chest tube simulators constructed from low-cost materials, but these do not enable adaptability of pleural fluid complexity, do not easily adapt to different patient habitus, and do not have ultrasound compatibility (11–13).

Three-dimensional printing (3DP) is a rapidly growing technology that may provide a cost-effective alternative. This technology makes it possible to print low-cost, three-dimensional models on the basis of computed tomography imaging, which has become increasingly recognized as an effective tool in health professions education with an emphasis on simulation. A systematic review of 3DP in surgical training demonstrated an accelerated procedural learning curve, improved anatomic knowledge acquisition, and shorter operation times for trainees (14), but 3DP technology has not been applied to pleural procedure simulation.

Objective

Given that performing a thoracentesis and other pleural procedures is dependent on the correct interpretation of tactile input, we aimed to create a pleural procedure simulator with characteristics of human tissue, at low cost and with ultrasound compatibility.

METHODS

Iterative Prototyping

Initial unstructured interviews with one interventional pulmonologist, two hospitalist medicine attending physicians on the procedural teaching service, and three pulmonary and critical care attending physicians provided a foundational understanding of current limitations of pleural procedure simulators. In partnership with the University of California, San Francisco, Makers Lab, we used a design-based research approach. Accordingly, the model was implemented and iteratively refined on the basis of feedback regarding each of the design components. The design theory and materials were discussed and developed iteratively with feedback from a group of design-based researchers at the University of California, Berkeley. Throughout the initial development process, 10 individuals piloted the initial pleural procedure model, including four pulmonary and critical care attending physicians, three IM residents, one pulmonary and critical care fellow, and two medical students. All individuals participated in an unstructured interview after using the model, in which they were asked specifically to comment on the realism of the skin, rib cage structure, resistance when passing a needle or catheter into the pleural space, and the feeling of pulling back fluid. In addition, participants were invited to comment on any changes, criticisms, or modifications they would recommend.

Deployment

In addition to the 10 individuals who tested and tried the model in the development phase, the initial version was formally piloted. Initial deployment consisted of one-on-one teaching sessions with three separate pairs of one pulmonary and critical care attending physician and one medical student. After the teaching session, both the attending physician and the student were asked to comment on experience and realism, providing specific points of feedback on the skin, ribs, and fluid pocket. Modifications were made according to this feedback. The modified simulator was deployed in two simulation sessions for a total of 40 IM residents (a mixture of second- and third-year residents), lasting one hour each. In addition, the simulator was used for two sessions for fourth-year medical students, in which a total of 16 students participated. After the simulations, stratified random sampling was used to select individuals to provide unstructured feedback on the simulator. In addition to the interviews, all residents who participated in the session were given an anonymous survey with the option for free-response feedback.

RESULTS

Iterative Prototyping

The three-dimensionally printed rib cage was developed using 3D Slicer (Brigham and Women's Hospital, Harvard Medical School) and Blender (Blender Foundation). The rib cage was printed using polylactic acid filament (Figure 1A). In the original version, a hemithorax with ribs 1 through 7 was printed. This was for practical reasons. As there are no major technical considerations between the right and left sides, printing only a hemithorax both saves on materials and makes the pleural cavity and fluid pocket accessible to modify and replace. On the subsequent iteration of the rib cage, shown in Figure 1D, only the lower ribs (ribs 6–12) were printed. This change was made because many thoracenteses are done in this region of the hemithorax. Given the shape of the lower border of the rib cage, as well as the need for stability, this second generation was fitted with a stand. The rib cage slots into three holes that then can be fastened in placed using a three-dimensionally printed nut and bolt system (Figure 1B). The base can then be clamped to the working surface to ensure that the model does not move while being worked on, and a base that accommodates different positioning (such as the lateral decubitus positioning) can be exchanged.

The fluid pocket and insert to keep it in place underwent multiple iterations (Figure 2). Version 1 (V1) of the fluid pocket insert was initially designed as a mesh backplate that clipped to the posterior aspect of the ribs, to hold a 250-ml saline bag in place (Figure 2A, V1). This backing was not robust enough to stay in place during puncture of the saline bag. It was remodeled to a rigid clip in the backplate (Figure 2A, V2). This was effective at holding the 250-ml saline bag

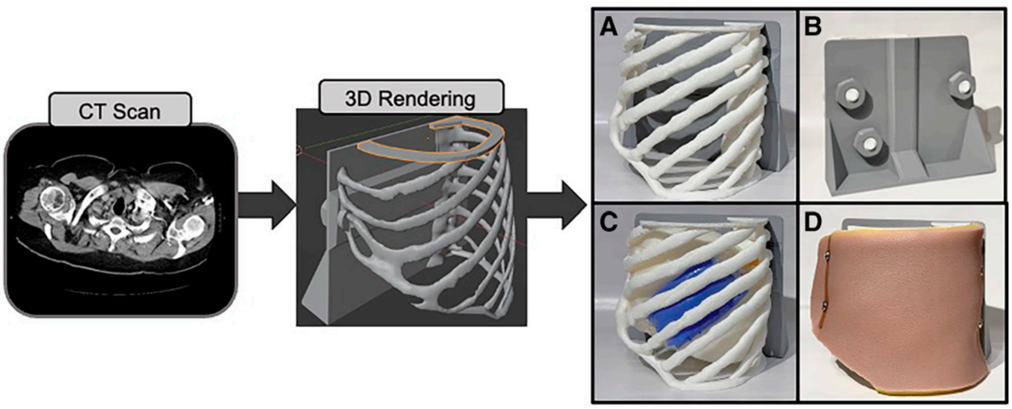

Figure 1. Three-dimensional (3D) rendering was extrapolated from a CT scan and was 3D printed using polylactic acid filament to provide a basic simulator structure. The rib cage was fitted with silicone skin and soft tissue, with a fluid-filled pouch to simulate pleural fluid. The design went through numerous iterations of skin/tissue attachment, rib cage mounting, and pleural fluid attachment to arrive at a model designed for easy setup, straightforward simulation teaching, and repeated use. (*A*) View of rib structure. (*B*) Backplate with nut/screw configuration for easy assembly. (*C*) Castable flexible urethane foam insert holding silicone coated fluid pocket in place. (*D*) Skin and fat layer fastened to the ribs in the completely assembled model. CT = computed tomography.

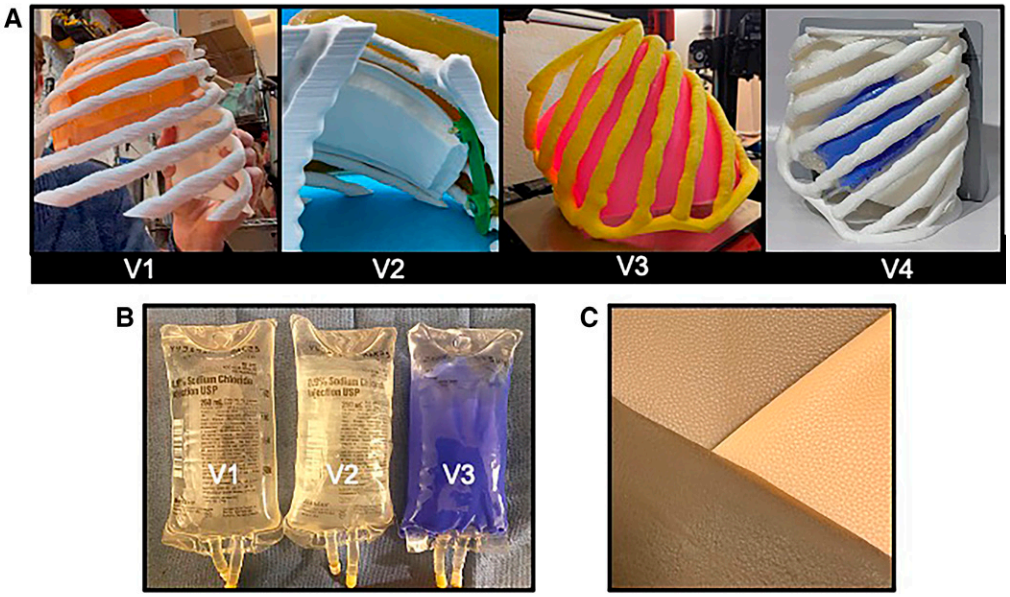

Figure 2. (*A*) The progression of the backplate to keep the fluid pocket in place evolved from version 1 (V1), a clip in flexible backing, to a rigid backplate (V2), then a flexible insert three-dimensionally printed using thermoplastic polyurethane (TPU) (V3), and finally a castable flexible urethane foam (V4) that was cast in the TPU printed insert. (*B*) The fluid pocket evolved from a simple 250-ml saline bag (V1), to a saline bag wrapped in silicone self-fusing plumbing tape (V2), with the final version coated with a paintable platinum cure silicone rubber (V3). (*C*) Silicone skin shown in multiple skin tones.

in place but could not accommodate bags of other sizes and was cumbersome to clip in place. To enable adaptability, a flexible insert was printed using thermoplastic polyurethane filament (Figure 2A, V3). This insert allows any size bag of fluid to be used and can be placed in any location within the rib cage. Thermoplastic polyurethane printing at a large scale, with respect to both the number and the size of the object printed, is prone to failure, so the fourth-generation insert is made of a castable flexible urethane foam to keep the fluid pocket in place, which is durable and provides enough tension to keep the fluid pocket in place even as fluid is removed from the model, shown in Figure 1C and 2A (V4).

For the actual fluid held by the insert, we used expired 250-ml saline bags, which are easily accessible in the healthcare environment (Figure 2B). Per feedback from the initial users, the saline bags did not offer quite enough resistance when being punctured, and they leaked readily after the first puncture, leading to rapid fluid loss. The second iteration involved wrapping the saline bags with silicone self-fusing plumbing tape, which added the needed resistance, reduced water leakage, and prolonged the life of the saline bag. One user reported "too much resistance" when passing a thoracentesis catheter into the pleural space. This wrapping method did not provide as much control over the thickness of the "pleura," so the third iteration was coated with a paintable platinum cure silicone rubber (Body Double, Smooth-On). This silicone layer creates a durable surface that provides enough resistance when being punctured to mimic the appropriate haptic feedback and can be added to the desired thickness to match the variable pleural pathology. In addition, this silicone has a self-healing property that allows it to withstand repeated needle punctures without leakage. There is some leakage with larger catheter placement (10 Fr or larger), but the rate of leakage is slow enough to facilitate a one-hour teaching session without issue. Users reported "you feel that double pop" when using this iteration, to describe the sensation of passing a needle into the pleural space.

From initial interviews, the dense skin was identified as a major limitation of commercially available pleural simulators. For our model, the rib cage was fitted with skin (which can be seen in multiple skin tones in Figure 2C) that was created using Ecoflex 00-30 silicone (Smooth-On) for the dermis layer and Ecoflex gel silicone for the fat and soft tissue layer. Silicone layers were colored with Silc Pig (Smooth-On) pigments. The soft tissue of a patient overlying the rib cage is more complex than the synthetic version used, with muscle and connective tissue, but the two-layer silicone skin was tested by eight separate individuals (two IM residents, three pulmonary and critical care attending physicians, and two pulmonary and critical care fellows) who reported that the skin offered realistic haptic feedback. Participants were given samples of various composition and asked to compare palpation of the synthetic skin overlying the three-dimensionally printed ribs with palpation of a person. They also punctured the various synthetic skin with needles, though no direct comparison with a needle puncture of human tissue was completed. To address the issue of ultrasound compatibility of the skin and fat layer, cellulose was added to increase the layer echogenicity to better mimic soft tissue. Ultimately, 1% by weight of cellulose was added to each layer, which provided appropriate visual feedback.

Ultrasound images from the pleural model are shown in Figure 3A. The soft tissue and parietal and visceral pleural lines are clearly shown, with an anechoic fluid pocket. Real-time ultrasound-guided needle advancement was similar to that seen in patients (Figures 3B and 3C). In addition, rib shadowing was seen (Figure 3D), similar to what is seen in patients.

The fourth-generation pleural simulator was created for $58.43. This cost is exclusive of labor and upfront costs to acquire a three-dimensional printer. The durable components that are reusable, such as the ribs and stand, amount to $23.65 of the production cost. Replacement fluid pockets cost $14.55 if using purchased saline bags, while replacement skin costs $34.78.

Deployment

After the one-on-one teaching sessions, during their interviews, all participants reported realistic haptic feedback from the skin and soft tissue and ribs of the pleural simulator, akin to the sensory feedback felt while performing a thoracentesis on a patient. One participant noted not enough resistance from the saline bag alone. This led to the transition to V3 with the paintable silicone coating, which increased the longevity of the fluid pocket and improved tactile sensation, as described above. Another user noted the limitation regarding ultrasound compatibility but reported that this was not a deterrent to using the three-dimensionally printed simulator in future teaching sessions.

After the resident simulation sessions, 29 of 40 (72.5%) participants responded to the survey, all stating that they would recommend the simulation session for others. Residents believed that the model was realistic and anecdotally reported increased confidence after use. The

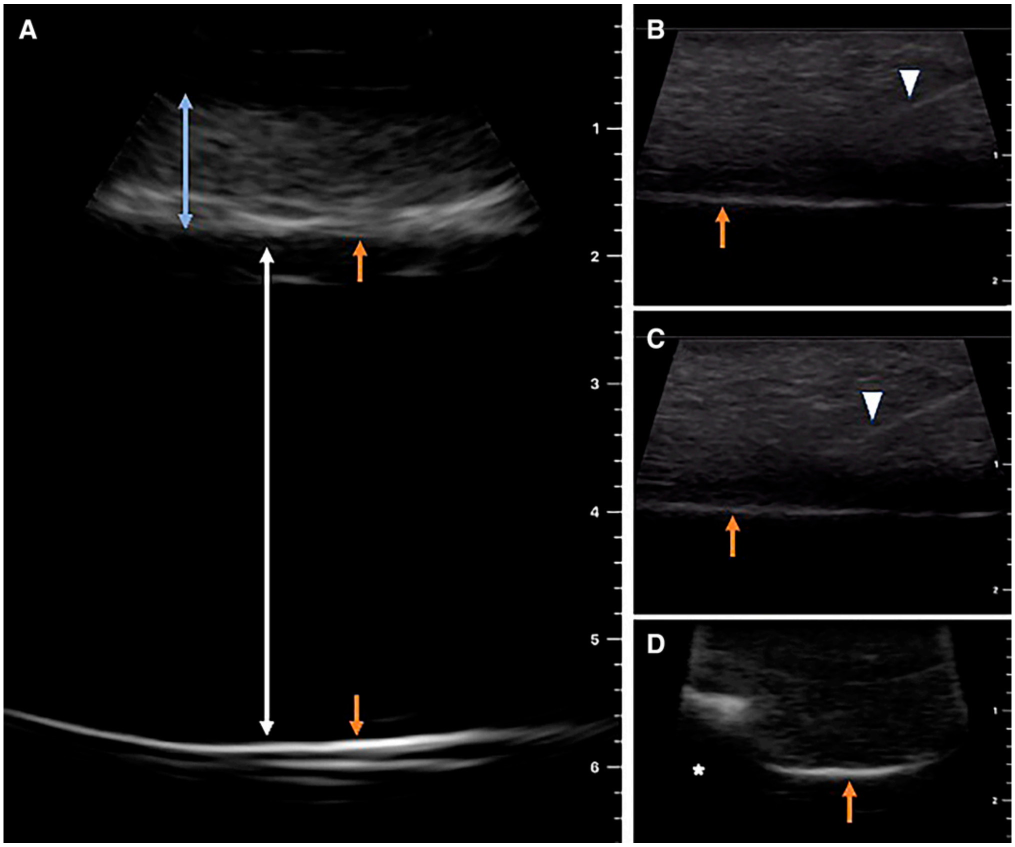

Figure 3. (*A*) Ultrasound view of simulator with soft tissue (blue arrow), fluid pocket (white arrows), and parietal and visceral pleural lines (orange arrows). (*B* and *C*) Close-up view of real-time needle advancement, with the tip of the needle denoted by an arrowhead and the pleural line indicated by an arrow. (*D*) Ultrasound view of pleural line (orange arrow) with rib shadow (asterisk).

medical students could not comment on realism, as none of them had performed a thoracentesis, but the use was universally reported as positive.

The current simulators have been used for more than 10 hours of simulation time, including transport and repeated setup and breakdown. All durable components (rib cage, stand, nuts, foam insert, and bands for skin attachment) remained intact without issue. The skin underwent innumerable needle insertions, at minimum 10 thoracenteses with 8-Fr catheters and four 14-Fr chest tube placements, without the need for replacement thus far. On average, each individual user used one saline bag during a simulation session.

DISCUSSION

We aimed to develop a low-cost, high-fidelity pleural procedure simulation alternative that provides tactile feedback more closely representing the characteristics of human tissue, affords ultrasound compatibility, and is adaptable to varying patient habitus and clinical conditions. This model specifically addresses the current limitations associated with traditional and currently available models. By leveraging the versatility of 3DP technology and commercially available silicones, we have successfully created a simulator that not only mimics the tactile feedback of human tissue but also accommodates ultrasound guidance and variability in patient anatomy. Our collaborative efforts, using design-based research and iterative prototyping, have culminated in a fourth-generation pleural simulator that provides realistic haptic feedback, is adaptable for teaching a range of pleural procedures, and is robust enough for repeated use.

This process highlighted the unique challenges of pleural procedure simulation. We opted to prioritize accurate haptic feedback over perfect ultrasonographic anatomic representation. The current model does allow for rib shadowing and visualization of the pleural line, but it does not allow for a diaphragmatic border or simulating consolidated lung within the effusion, for example. We believe that lung ultrasound is an additional skill set that can be taught at the bedside with minimal risk to patients. Furthermore, in the feedback sessions from residents, they were most uncomfortable not with ultrasound but with the physical skill of inserting a catheter. This choice was also made from a practical and economic standpoint, as the complexity and cost of achieving perfect ultrasound fidelity may be prohibitive to simulator production.

Future efforts in pleural simulator development are focused on the texture and consistency of the skin and pleural surface to facilitate advanced pleural procedures, such as pleuroscopy, together with the development of a skin and soft tissue texture that provides appropriate tactile feedback for blunt dissection. Additional work will focus on creating complex pleural pockets, with adhesions and loculations, to further facilitate simulation training for more clinically complex patients.

We currently have five total fourth-generation simulators in active use for medical student and resident simulation. Step-by-step instruction for the creation of this novel tool is included in the data supplement, together with open-source .stl files for printing. We hope that other institutions with 3DP capabilities are able to download and produce their own low-cost simulators to be deployed at their own medical centers, thus transforming the ability to include just-in-time procedural training for thoracentesis on a much larger scale than previously possible. Future directions will focus on side-by-side comparison with current commercially available models, as well as impact on skill transferability and decay.

Conclusions

The development of a low-cost, high-fidelity pleural procedure simulator addresses the current limitations of commercially available pleural simulators. By integrating 3DP technology and easily accessible materials, we were able to produce a simulator that not only closely replicates the feel of human tissue and allows ultrasound use but is also adaptable for different patient anatomies and clinical scenarios. This novel simulator may be a scalable solution to elevate the standard of procedural education and ultimately positively affect patient care.

Author disclosures are available with the text of this article at www.atsjournals.org.

REFERENCES

1. Sawyer T, White M, Zaveri P, Chang T, Ades A, French H, *et al.* Learn, see, practice, prove, do, maintain: an evidence-based pedagogical framework for procedural skill training in medicine. *Acad Med* 2015;90:1025–1033.

2. Jhaveri VV, Currier PF, Johnson JH. Bridging the gap between “do one” and “teach one”: impact of a procedural objective structured teaching encounter on resident procedural teaching proficiency. *Med Sci Educ* 2020;30:905–910.

3. Al-Elq AH. Simulation-based medical teaching and learning. *J Family Community Med* 2010;17: 35–40.

4. Cook DA, Hatala R, Brydges R, Zendejas B, Szostek JH, Wang AT, *et al.* Technology-enhanced simulation for health professions education: a systematic review and meta-analysis. *JAMA* 2011;306: 978–988.

5. McGaghie WC, Issenberg SB, Barsuk JH, Wayne DB. A critical review of simulation-based mastery learning with translational outcomes. *Med Educ* 2014;48:375–385.

6. Barsuk JH, Cohen ER, Williams MV, Scher J, Jones SF, Feinglass J, *et al.* Simulation-based mastery learning for thoracentesis skills improves patient outcomes: a randomized trial. *Acad Med* 2018;93:729–735.

7. Wayne DB, Barsuk JH, O’Leary KJ, Fudala MJ, McGaghie WC. Mastery learning of thoracentesis skills by internal medicine residents using simulation technology and deliberate practice. *J Hosp Med* 2008;3:48–54.

8. Mourad M, Kohlwes J, Maselli J, Auerbach AD, Auerbach AD; MERN Group. Supervising the supervisors—procedural training and supervision in internal medicine residency. *J Gen Intern Med* 2010;25:351–356.

9. Huang GC, Smith CC, Gordon CE, Feller-Kopman DJ, Davis RB, Phillips RS, *et al.* Beyond the comfort zone: residents assess their comfort performing inpatient medical procedures. *Am J Med* 2006;119:71.e17–24.

10. Kouyoumjian S, Velilla MA, Paxton JH. A novel simulation model for tube thoracostomy. *SAGE Open Med* 2023;11:20503121231178336.

11. Young TP, Schaefer MD, Kuntz HM, Estes MK, Kiemeney M, Wolk BJ, *et al.* Yogaman: an inexpensive, anatomically-detailed chest tube placement trainer. *West J Emerg Med* 2019;20: 117–121.

12. Crawford SB, Huque YI, Austin DE, Monks SM. Development and review of the Chest Tube High-Feedback Educational Simulation Trainer (CHEST). *Simul Healthc* 2019;14:276–279.

13. Al-Qadhi SA, Pirie JR, Constas N, Corrin MS, Ali M. An innovative pediatric chest tube insertion task trainer simulation: a technical report and pilot study. *Simul Healthc* 2014;9:319–324.

14. Langridge B, Momin S, Coumbe B, Woin E, Griffin M, Butler P. Systematic review of the use of 3-dimensional printing in surgical teaching and assessment. *J Surg Educ* 2018;75:209–221.