

A collaboration between the JAOA and the American Association of Colleges of Osteopathic Medicine (AACOM) to recruit, peer review, publish, and distribute research and other scholarly articles related to osteopathic medical education.

JAOA/AACOM

Developing Neuraxial and Regional Pain Procedural Skills Through Innovative 3-Dimensional Printing Technology

Zachary C. Headman, BA, OMS III; Marcus C. Matson, BS, OMS III; Robert P. Schneider, DO; James L. Potter, DO; Debra L. Loguda-Summers, CLSS; Shalini Bhatia, MS; Tatyana Kondrashova, MD, PhD

From the Departments of Family Medicine, Preventive Medicine, and Community Health (Drs Schneider and Kondrashova) and Surgery (Dr Potter) at A. T. Still University Kirksville College of Osteopathic Medicine in Missouri (Student Doctors Headman and Matson) and the A.T. Still Memorial Library (Ms Loguda-Summers) and the Department of Research Support (Ms Bhatia) at A.T. Still University in Kirksville, Missouri.

Financial Disclosures:
None reported.

Support: Supported by a grant from the A.T. Still University Spark Tank Challenge, grant No. 501-620.

Address correspondence to Tatyana Kondrashova, MD, PhD, Kirksville College of Osteopathic Medicine, 800 W Jefferson St, Kirksville, MO, 63501-1443.

Email:
tkondrashova@atsu.edu

Submitted
June 13, 2019;
revision received
August 22, 2019;
accepted
September 17, 2019.

Context: Various forms of simulation-based training, including training models, increase training opportunities and help assess performance of a task. However, commercial training models for lumbar puncture and epidural procedures are costly.

Objective: To assess medical students' and residents' perception of 3-dimensional (3D)-printed lumbar, cervical, and pelvic models for mastering joint injection techniques and to determine the utility of ultrasonography-guided needle procedure training.

Methods: Osteopathic medical students and residents used in-house 3D-printed gel joint models during an injection ultrasonography laboratory for mastering lumbar epidural, caudal epidural, sacroiliac, and facet joint injection techniques. After the laboratory, they answered a 17-item survey about their perception of the importance of the models in medical education and future practice. The survey also evaluated comfort levels with performing joint injections after using the models, overall satisfaction with the models, and likelihood of using models in the future.

Results: Thirty-six medical students and residents participated. Both students and residents agreed that 3D-printed models were easy to use, aided understanding of corresponding procedures, and increased comfort with performing joint injections (all $P < .001$). Most participants (35 [97.2%]) believed that the models were reasonable alternatives to commercial models. Over half felt capable of successfully performing cervical or pelvic (22 [61.1%]) and lumbar epidural (23 [63.9%]) injections. The majority of participants (34 [94.4%]) would like to use the models in the future for personal training purposes. Overall, 100% believed that the 3D-printed models were a useful tool for injection training.

Conclusions: Results suggest that 3D-printed models provided realistic training experience for injection procedures and seemed to allow participants to quickly master new injection techniques. These models offer a visual representation of human anatomy and could be a cost-saving alternative to commercial trainers.

J Am Osteopath Assoc. 2020;120(4):273-282
doi:10.7556/jaoa.2020.044

Keywords: anatomy, injection procedures, 3D printing

Primary care physicians frequently treat patients with musculoskeletal and joint conditions; intra-articular injection treatment for these conditions requires comfort, confidence, and skill. Equally important in outpatient and inpatient settings, this skill set requires injection and ultrasonography-guided needle proficiencies.^{1,2} The combination of these proficiencies can make mastery of this skill set challenging, but an advantage of using ultrasonography for injections is the ability to confirm exact placement.³ Ultrasonography frees the physician from using “blind techniques” and surface landmarks during injections and avoids complications from variations in anatomy⁴ and physiology.⁵ The accuracy of injections performed with ultrasonography positively affects success rates and reduces the number of complications, especially those associated with obesity and edema.⁶ Ultrasonography also reduces health care costs and has no association with radiation exposure.^{7,8}

Injections are common medical procedures across a variety of specialties. Neuraxial anesthesia and joint injections for regional pain control are commonly performed by anesthesiologists and other physicians.⁴⁶ However, proper injection technique training and instruction are limited during formal medical training.

Medical students spend hours studying disease processes of the human body and how to properly manage them. During formal training, they are expected to practice that knowledge through rotations and residency training.⁹ A common method during training is the “see one, do one, teach one” model.¹⁰ However, this method creates additional challenges that may be detrimental to patient care by increasing patient discomfort and delaying time to treatment.¹¹ When learning proper needle handling and injection techniques, this method can be distressing for patients and have negative consequences.¹² Fortunately, various forms of simulation, including training models, increase training opportunities and help assess performance of a task.¹³

Ultrasonography training models allow the learner to acquire technical clinical skills through repeated prac-

tice,^{14,15} and they can be physical models, computer programs, or both. The most common training models are commercial phantoms, which can be scanned and allow visualization of needle placement. Lifelike ultrasonography models use tissue technology compatible with diagnostic ultrasonography systems and provide realistic training and assessment without the risk, inconvenience, and expense of standardized patients.¹⁶ The lifelike feel allows mastery of proper procedure mechanics before trainees progress to procedures on real patients.¹⁷ Previous studies have indicated that ultrasonography training models significantly improve learning outcomes¹⁸⁻²¹ and may be superior to traditional methods.^{22,23} Furthermore, simulation-based ultrasonography training of postgraduate physicians improved clinical competence.^{20,24-28}

Advances in segmentation software²⁹ make it easy to extract the surface of structures from 3-dimensional (3D) medical imaging data and generate anatomical models. Accessibility to 3D printers and advanced segmentation algorithms have increased the use of 3D printing for multiple medical applications.³⁰⁻³³ Currently, 3D printing is used in various health care settings^{34,35} and allows quick, easy reproduction of complex anatomical structures at an affordable cost.^{36,37} Therefore, 3D-printed training models may be a more affordable and better alternative to commercial models.³⁸ This technology allows models of the human body to be 3D-printed for teaching kidney,³² heart,³⁹ and liver⁴⁰ procedures. Previous studies have also described model use for research and training of procedures related to vessels,^{41,42} parts of the skull,⁴³ the optic nerve,⁴⁴ and renal system.⁴⁵

The primary objectives of the current study were to assess medical students' and residents' perception of 3-dimensional (3D)-printed lumbar, cervical, and pelvic models for mastering joint injection techniques and to determine the utility of ultrasonography-guided needle procedure training. We hypothesized that the models would be well received by medical students and residents and would help them in mastering joint injection techniques.

Methods

Third- and fourth-year osteopathic medical students from A.T. Still University Kirksville College of Osteopathic Medicine and residents from Northeast Regional Medical Center were invited to participate in the study. Participation was voluntary. Residency types included internal medicine, anesthesia, osteopathic manipulative medicine, and family medicine. Participants used 3D-printed medical gel joint models made in-house for mastering joint injection techniques with ultrasonography guidance. The A.T. Still University-Kirksville institutional review board granted exempt status for all educational procedures used in the current study.

Three new models were developed and used in the current study (**Figure 1**). The cervical spine model included 7 cervical vertebrae with spinous and transverse processes, intervertebral discs, nerves, and vasculature. The lumbar puncture/spinal epidural model contained lumbar vertebrae L1-L5, intervertebral discs, ligamenta flava, epidural space, and subarachnoid space with cerebrospinal fluid. The pelvic model contained os coxae, lumbar vertebrae L4 and L5, intervertebral discs,

nerves, sacrum, coccyx, ilium, sacroiliac joints, and posterior superior iliac spine.

Flexible intervertebral discs, nerves, and vasculature were printed using Cheetah flexible filaments (NinjaTek, Fenner Inc.) on an Afinia 3D printer. A Stratasys F123 Series: F170 printer was used to print the vertebrae, pelvis, and sacrum with acrylonitrile butadiene styrene filaments. After the models were printed and cleaned in an SCA-1200HT support removal system (Phoenix Analysis & Design Technologies), they were assembled using Gorilla glue gel and small screws. The printed nerves, vasculature, and rubber tubing (representing the spinal cord) were placed in their proper anatomical position. Some of the models were then coated with high-temperature silicone to minimize bubbles. The models were attached with screws to wooden stands to support them in the proper anatomical position.

Humimic Gel #0 (Humimic Medical Healthcare Products) is one of the most versatile gelatins used for medical imaging. The gel is clear and produces realistic tissue-like texture when imaged with ultrasonography. This gel was used to encase the models so blind insertion and ultrasonography-guided techniques could be used for injection procedures on all of the models. Molds were designed using aluminum sheet metal and flue pipe to ensure the proper shape and size for each model. The molds were attached to the wooden bases around the models with high-temperature fireplace sealant, flue tape, and steel duct clamps to ensure that the hot liquid gel did not leak. The gel was cut into small pieces and melted in 3-pound increments at 121°C. Once melted, it was poured into each mold and allowed to cool. Once the gel cooled and solidified, an electric heated knife and hot air gun were used to sculpt the molds into proper anatomical shapes.

The completed models were used in injection technique laboratories that taught needle-guidance procedures with the use of ultrasonography. Before participating in the laboratory, medical students and residents of the current study mastered basic ultrasonography techniques and applications through clinical

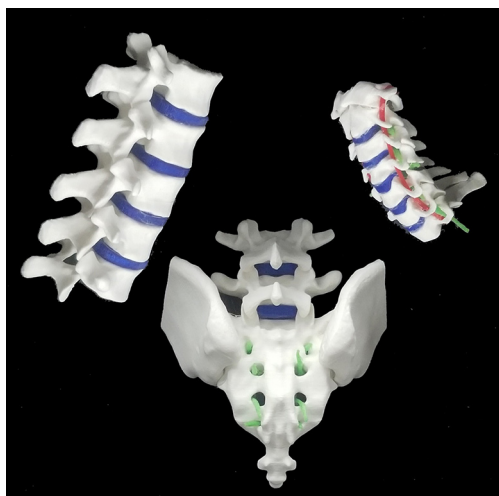


Figure 1. Cervical, lumbar, and pelvic 3D-printed models used in the joint injection technique laboratory.

ultrasonography coursework and monthly didactic ultrasonography sessions.²² The laboratory began with a presentation that explained the objectives and clinical relevance of the injection exercise. The presentation was followed by a live demonstration of the injection technique and ultrasonography scanning technique using the 3D-printed models (**Figure 2**). The models are also ideal for ultrasonography-guided techniques because the gel produces a realistic tissue-like texture when imaged. Participants used Mindray-5 ultrasonography machines with 10L4s linear ultrasonography

transducer and a frequency bandwidth of 8.0/10.0/12.0 MHz (Shenzhen Mindray Bio-Medical Electronics Co.).

The objective of the injection ultrasonography laboratory was to identify anatomical structures of interest and perform injections. Students and residents had to identify the following anatomical structures to perform injections: C1-C7 spinous and transverse processes and facet joints on the cervical model; L1 through L5 spinous processes on the lumbar puncture model; and L4 and L5 spinous processes, sacroiliac joints, and caudal epidural region on the pelvic model.

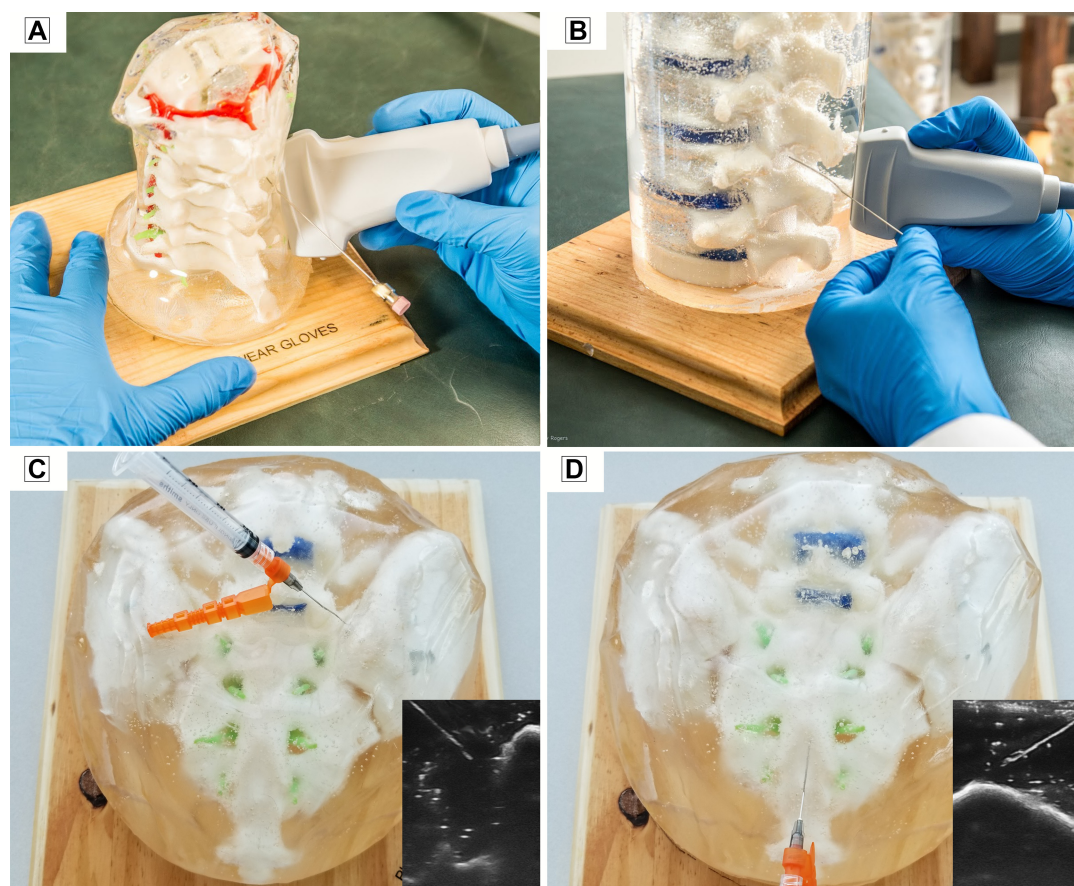


Figure 2.

Spine and pelvic models used in the joint injection technique laboratories. (A) 3D-printed medical gel cervical model with the needle showing facet joint access; (B) 3D-printed medical gel lumbar model with the needle showing lumbar/epidural access; (C) 3D-printed medical gel pelvic model with the needle showing sacroiliac joint access, where the inset shows the ultrasonography image indicating the needle position; (D) 3D-printed medical gel pelvic model with the needle showing caudal epidural access, where the inset shows the ultrasonography image indicating the needle position.

After the training laboratory, participants were asked to complete a 17-item paper survey about their perceptions of the importance of the models for education and future practice. The survey was created specifically for the current study by the course director for the Clinical Ultrasonography course; it was voluntary, anonymous, and did not collect demographic information. The survey was validated using predoctoral fellows (completed 2 years of medical school, taking a year off to help faculty teach courses) to verify, items were readable, and interpreted consistently. Fifteen items were Likert-scale (strongly disagree, disagree, neither agree nor disagree, agree, and strongly agree) items. Those items evaluated participant comfort level with performing joint injections after using the models with ultrasonography needle guidance, overall satisfaction with the models, and likelihood of using 3D models in the future. Items also asked participants to compare commercial injection training models with the in-house 3D models (feel, anatomical correctness, and comfort when using the models). The last 2 survey items were open-ended items that asked, “What is one thing you would like to see as part of the Injection Lab regarding the use of simulation models that we did not include?,” and “Please leave comments about the use of 3D-printed models in medical education.”

The current study used a sample of convenience, so no formal sample size calculation was performed. Total scores for the 15 Likert-scale items (where strongly agree was defined as 5 and strongly disagree was defined as 1) were calculated for all participants. Survey responses were summarized with frequencies and percentages. Agree and strongly agree responses were combined and defined as suggesting agreement. Disagree and strongly disagree responses were also combined and defined as suggesting disagreement. A χ^2 test was used to compare the proportion of agreement between students and residents. The binomial test of proportion was used to compare the proportions of agreement and disagreement for all individual survey items. Data analysis was completed using SAS

version 9.4 (SAS Institute, Inc.). $P \leq .05$ was considered statistically significant.

Results

Fifteen medical students and 21 residents completed the survey. Combining all survey items for students and residents separately, 14 (94.7%) students and 18 (87.3%) residents agreed, no students and 1 (3.2%) resident disagreed, and 1 (5.3%) student and 2 (9.5%) residents were neutral on the importance of 3D-printed models for injection training ($P = .004$).

Responses for all participants on all survey items are summarized in the [Table](#). For defined agreement responses, all participants thought that the 3D-printed models were easy to use, while a majority (34 [94.4%]) thought that they were a useful tool to provide injection training and that they increased participant comfort in performing joint injections (28 [77.8%]). Students and residents (35 [97.2%]) agreed the models were a reasonable alternative to commercial training models (22 [61.1%]) felt capable of successfully performing cervical and/or pelvic injections, and 23 (63.9%) felt capable of successfully performing a lumbar/epidural procedure. Most participants (34 [94.4%]) would have liked to use the 3D-printed models in the future for personal training purposes.

The majority believed that lumbar/epidural (34 [94.4%]), cervical facet joints (34 [94.4%]), sacroiliac (35 [97.2%]), and caudal epidural (34 [94.4%]) procedure training helped them better understand the injections with ultrasonography guidance and that the models would help them in their future practice and for development of their clinical skills (both 34 [94.4%]) ([Table](#)). They also believed that the 3D-printed models could improve the existing medical curriculum (35 [97.2%]).

Participant responses to the open-ended items indicated students felt more prepared for rotations and residents felt more confident about performing injection procedures later during their residency. Participants also indicated that visualizing anatomical structures

Table.
Survey Responses of Third- and Fourth-Year Medical Students and Residents About Their Perceptions of the Importance of the 3D-Printed Models for Joint Injection Techniques^a

Survey Item	Strongly Agree or Agree	Neither Agree Nor Disagree	Disagree or Strongly Disagree	P Value
The 3D-printed models were easy to use.	36 (100)	0 (0)	0 (0)	<.001
I believe the 3D-printed models are a useful tool to provide lumbar/epidural procedure training.	34 (94.4)	2 (5.6)	0 (0)	<.001
Using ultrasonographic guidance with the 3D-printed lumbar model helped me better understand lumbar and epidural procedures.	34 (94.4)	1 (2.8)	1 (2.8)	<.001
Using ultrasonographic guidance with the 3D-printed cervical and lumbar models helped me better understand facet joint injections.	34 (94.4)	1 (2.8)	1 (2.8)	<.001
Using ultrasonographic guidance with the 3D-printed pelvic model helped me better understand sacroiliac joint injections.	35 (97.2)	0 (0)	1 (2.8)	<.001
Using ultrasonographic guidance with the 3D-printed sacral model helped me better understand caudal epidural injections.	34 (94.4)	1 (2.8)	1 (2.8)	<.001
The 3D-printed models are a reasonable alternative to the commercial training models.	35 (97.2)	1 (2.8)	0 (0)	<.001
I believe the 3D-printed models are a useful tool to provide injection training.	36 (100)	0 (0)	0 (0)	<.001
Using ultrasonographic guidance with the 3D-printed models increased my comfort performing joint injections.	28 (77.8)	8 (22.2)	0 (0)	<.001
I feel capable of successfully performing cervical and/or pelvic injections.	22 (61.1)	12 (33.3)	2 (5.6)	.18
I feel capable of successfully performing a lumbar/epidural procedure.	23 (63.9)	11 (30.6)	2 (5.6)	.09
I would like to use the 3D-printed models in the future for my personal training purposes.	34 (94.4)	2 (5.6)	0 (0)	<.001
The use of the 3D-printed models was beneficial for development of my clinical skills.	34 (94.4)	2 (5.6)	0 (0)	<.001
Using the 3D-printed models with ultrasonographic guidance will help me in my future practice.	34 (94.4)	1 (2.8)	1 (2.8)	<.001
I believe the 3D-printed models could improve the existing medical curriculum.	35 (97.2)	0 (0)	1 (2.8)	<.001

^a Data are given as No. (%) unless otherwise indicated.

Abbreviation: 3D, 3-dimensional.

inside the clear-gel models augmented their understanding of anatomy and the clinical relevance of the procedures. Overall, responses to the open-ended survey items seemed to suggest that participants were overwhelmingly positive about the incorporation of 3D-printed models in their education.

Discussion

In the current study, third- and fourth-year medical students and residents used in-house 3D-printed gel models for mastering joint injection techniques with ultrasonography guidance. Both students and residents agreed that 3D-printed models were helpful and easy to use, aided understanding of corresponding procedures, and increased comfort performing joint injections. Most believed that the new models were reasonable alternatives to commercial models, and more than half felt capable of successfully performing a lumbar epidural procedure and cervical or pelvic injections. All participants believed that 3D-printed models were a useful tool for injection training, and some indicated they would like to use the models in future for personal training purposes. The 3D-printed models developed for our study provided the same realistic feel for the various procedures as the commercial models, but had an additional benefit of allowing the trainees to visualize the key anatomical structures and their spatial relationships because of the transparent gel used as the model matrix. This visual and tactile feedback allowed trainees greater understanding of where they were in the body and what they were feeling.⁴⁷ Future models could have a skinlike layer to be more realistic and provide a more challenging and authentic injection experience.

Although simulation in medical training is well established⁴⁸ and efficient for emergency medicine, trauma, surgery, and critical care,^{22,49,50} the upfront cost and associated maintenance of current commercial training models are limiting factors.⁵¹ Thus, students have reduced exposure to models during training, which places the burden of student education back

onto the patient. More affordable training models would allow more access for students to learn and master various procedural skills, including needle handling.⁵² The use of 3D printing may be one way to reduce costs, as each model costs \$400 to \$500 USD to produce, which is a tenth of the cost of a commercial trainer.

With the increasing use of ultrasonography in medicine, ultrasonography-guided procedures are quickly becoming the standard of care.⁶ The 3D-printed models developed for the current study were specifically made with materials that were compatible with ultrasonography and allowed for the visualization of all anatomic structures. Thus, students and residents had the opportunity to master procedures with or without image guidance. Mastery of injection skills is critical for patient safety and physician proficiency in order to avoid medical errors in future practice.

Previous research findings have highlighted the importance of simulation-based medical education: students trained to use ultrasonography with virtual trainers were better prepared to interpret images than classroom-based learners.⁵³ Results of the current study are consistent with these data. The 3D models allowed medical students and residents to visually identify skeletal structures on the models and on ultrasonography images since the surrounding medical gel was clear. This visual identification of skeletal structures augmented with ultrasonography increased participants' confidence with the injection techniques and ultrasonography image interpretation. All participants were able to obtain images of the lumbar spine, facet joints, sacroiliac joints, and caudal epidural area, and the majority believed that the training models helped them better understand ultrasonography guidance for injections.

The most challenging procedures in the current study were lumbar epidural and cervical injections; 61% of participants felt capable of successfully performing cervical and/or pelvic injections, and 64% felt capable of successfully performing a lumbar/epidural procedure. These results correlate well with published data that indicated lumbar epidural injections presented major

procedural challenges to practitioners with limited experience.⁵⁴⁻⁵⁸

The ability to correctly perform injection procedures is an important aspect of medical training because it affects physician competence and patient safety. In one study,⁵⁹ physicians trained with simulation-based techniques outperformed and were more competent than traditionally trained physicians for a specific procedure. The use of simulation-based education also improved patient safety.⁵⁹ Given these benefits, it is important to begin simulation training at the undergraduate medical student level and continue this training during residency.

Results of the current study showed that most participants believed that the new 3D-printed models could improve the existing medical curriculum and were beneficial for the development of clinical skills, which is consistent with current reviews of the role of simulation in medical education.⁵⁹ Both students and residents believed that training with 3D-models aided their future practice, which indicates that participants were receptive to incorporating the models as a new technology into their education. Participants reported that being able to visualize anatomical structures inside the clear-gel models augmented their understanding of anatomy and the clinical relevance of the procedures. Future studies should consider using dyes with the needle-guided techniques, so trainees could also see how medications spread after injection.

This study was limited by its small size. Sample size was restricted by the number of third- and fourth-year medical students and residents at the study site. Future studies should include a large sample size or a use multi-institutional approach. Other limitations are that we did not use a control group or perform quality assurance on the manufactured models. Our survey was created specifically for the current study and was not validated.

Conclusion

Our results suggested that 3D-printed models provided realistic training for injection procedures and may

serve as a cost-saving alternative to commercial training models. This training could begin at the undergraduate medical student level and progress through residency. The 3D-printed spine and pelvic models were well received by both medical students and residents. Furthermore, the models seemed to allow the trainees to quickly master injection techniques, which would potentially improve their future patient care.

Acknowledgments

We thank Deborah Goggin, MA, ELS, Scientific Writer at A.T. Still University, for help with manuscript preparation, and Jamie Carroll, BFA, Senior Graphic Artist at A.T. Still University, for help with 3D printing.

Author Contributions

All authors provided substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; all authors drafted the article or revised it critically for important intellectual content; all authors gave final approval of the version of the article to be published; and all authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

References

1. Morisky DE, Ang A, Krousel-Wood M, Ward HJ. Predictive validity of a medication adherence measure in an outpatient setting. *J Clin Hypertens (Greenwich)*. 2008;10(5):348-354. doi:10.1111/j.1751-7176.2008.07572.x
2. Lininger RA. Pediatric peripheral IV insertion success rates. *Pediatr Nursing*. 2003;29(5):351-355.
3. Hopkins PM. Ultrasound guidance as a gold standard in regional anaesthesia. *Br J Anaesth*. 2007;98(3):299-301. doi:10.1093/bja/ael387
4. Retzl G, Kapral S, Greher M, Mauritz W. Ultrasonographic findings of the axillary part of the brachial plexus. *Anesth Analg*. 2001;92(5):1271-1275. doi:10.1097/0000539-200105000-00037
5. Perlas A, Niazi A, McCartney C, Chan V, Xu D, Abbas S. The sensitivity of motor response to nerve stimulation and paresthesia for nerve localization as evaluated by ultrasound. *Reg Anesth Pain Med*. 2006;31(5):445-450. doi:10.1016/j.rapm.2006.05.017
6. Marhofer P, Greher M, Kapral S. Ultrasound guidance in regional anaesthesia. *Br J Anaesth*. 2004;94(1):7-17. doi:10.1093/bja/ael002
7. Moore CL, Copel JA. Point-of-care ultrasonography. *N Engl J Med*. 2011;364(8):749-757. doi:10.1056/NEJMra0909487
8. Brenner DJ, Hall EJ. Computed tomography: an increasing source of radiation exposure. *N Engl J Med*. 2007;357(22):2277-2284. doi:10.1056/NEJMra072149
9. Long DM. Competency-based residency training: the next advance in graduate medical education. *Acad Med*. 2000;75(12):1178-1183. doi:10.1007/978-3-7091-6237-8_28

10. Vozenilek J, Huff JS, Reznick M, Gordon JA. See one, do one, teach one: advanced technology in medical education. *Acad Emerg Med*. 2004;11(11):1149-1154. doi:10.1197/j.aem.2004.08.003
11. Lenchus JD. End of the "see one, do one, teach one" era: the next generation of invasive bedside procedural instruction. *J Am Osteopath Assoc*. 2010;110(6):340-346.
12. Rodriguez-Paz J, Kennedy M, Salas E, et al. Beyond "see one, do one, teach one": toward a different training paradigm. *Qual Saf Health Care*. 2009;18(1):63-68. doi:10.1136/qshc.2007.023903
13. Magee D, Zhu Y, Ratnalingam R, Gardner P, Kessel D. An augmented reality simulator for ultrasound guided needle placement training. *Med Biol Eng Comput*. 2007;45(10):957-967. doi:10.1007/s11517-007-0231-9
14. Kneebone R. Simulation in surgical training: educational issues and practical implications. *Med Educ*. 2003;37(3):267-277. doi:10.1046/j.1365-2923.2003.01440.x
15. Kondrashova T, Coleman C. Enhancing learning experience using ultrasound simulation in undergraduate medical education: student perception. *Med Sci Educ*. 2017;27(3):489-496.
16. Issenberg SB, Scalese RJ. Simulation in health care education. *Perspect Biol Med*. 2008;51(1):31-46. doi:10.1353/pbm.2008.0004
17. Wang EE, Quinones J, Fitch MT, et al. Developing technical expertise in emergency medicine: the role of simulation in procedural skill acquisition. *Acad Emerg Med*. 2008;15(11):1046-1057. doi:10.1111/j.1553-2712.2008.00218.x
18. Yoo MC, Villegas L, Jones DB. Basic ultrasound curriculum for medical students: validation of content and phantom. *J Laparoendosc Adv Surg Tech A*. 2004;14(6):374-379. doi:10.1089/lap.2004.14.374
19. Daftari AP, Jaffer J, Homer SH, Schaefer MP. Bovine shoulder and hip models to teach ultrasound-guided injections. *A J Physical Med Rehabil*. 2011;90(9):746-755. doi:10.1097/PHM.0b013e31820b15fd
20. Maul H, Scharf A, Baier P, et al. Ultrasound simulators: experience with the SonoTrainer and comparative review of other training systems. *Ultrasound Obstet Gynecol*. 2004;24(5):581-585. doi:10.1002/uog.1119
21. Miller GT, Scerbo MW, Zybak S, et al. Learner improvement from a simulation-enhanced ultrasonography curriculum for first-year medical students. *J Ultrasound Med*. 2017;36(3):609-619. doi:10.7863/ultra.15.12025
22. McGaghie WC, Issenberg SB, Cohen MER, Barsuk JH, Wayne DB. Does simulation-based medical education with deliberate practice yield better results than traditional clinical education? A meta-analytic comparative review of the evidence. *Acad Med*. 2011;86(6):706-711. doi:10.1097/ACM.0b013e318217e119
23. McGaghie WC, Issenberg SB, Petrusa ER, Scalese RJ. A critical review of simulation-based medical education research: 2003-2009. *Med Educ*. 2010;44(1):50-63. doi:10.1111/j.1365-2923.2009.03547.x
24. Berkenstadt H, Erez D, Munz Y, Simon D, Ziv A. Training and assessment of trauma management: the role of simulation-based medical education. *Anesthesiol Clin*. 2007;25(1):65-74. doi:10.1016/j.atc.2006.11.004
25. 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(1):48-54. doi:10.1002/jhm.268
26. Silva JP, Plescia T, Molina N, Tonelli AC, Langdorf M, Fox JC. Randomized study of effectiveness of computerized ultrasound simulators for an introductory course for residents in Brazil. *J Educ Eval Health Prof*. 2016;13:16. doi:10.3352/jeehp.2016.13.16
27. Mendiratta-Lala M, Williams T, de Quadros N, Bonnett J, Mendiratta V. The use of a simulation center to improve resident proficiency in performing ultrasound-guided procedures. *Acad Radiol*. 2010;17(4):535-540. doi:10.1016/j.acra.2009.11.010
28. Parks AR, Atkinson P, Verheul G, LeBlanc-Duchin D. Can medical learners achieve point-of-care ultrasound competency using a high-fidelity ultrasound simulator? a pilot study. *Crit Ultrasound J*. 2013;5(1):9. doi:10.1186/2036-7902-5-9
29. Withey DJ, Koles ZJ. Medical image segmentation: methods and software. Paper presented at: 2007 Joint Meeting of the 6th International Symposium on Noninvasive Functional Source Imaging of the Brain and Heart and the International Conference on Functional Biomedical Imaging; Oct 12-14, 2007; Hangzhou, China.
30. Bücking TM, Hill ER, Robertson JL, Maneas E, Plumb AA, Nikitichev DI. From medical imaging data to 3D printed anatomical models. *PLoS One*. 2017;12(5):e0178540. doi:10.1371/journal.pone.0178540
31. Rengier F, Mehndiratta A, Von Tengg-Kobligh H, et al. 3D printing based on imaging data: review of medical applications. *Int J Comput Assist Radiol Surg*. 2010;5(4):335-341.
32. Kusaka M, Sugimoto M, Fukami N, et al. Initial experience with a tailor-made simulation and navigation program using a 3-D printer model of kidney transplantation surgery. *Transplant Proc*. 2015;47(3):596-599. doi:10.1016/j.transproceed.2014.12.045
33. Trace AP, Ortiz D, Deal A, et al. Radiology's emerging role in 3-D printing applications in health care. *J Am Coll Radiol*. 2016;13(7):856-862.e854. doi:10.1016/j.jacr.2016.03.025
34. Mitsouras D, Liacouras P, Imanzadeh A, et al. Medical 3D printing for the radiologist. *Radiographics*. 2015;35(7):1965-1988. doi:10.1148/rgr.2015140320
35. Bortman J, Baribeau Y, Jeganathan J, et al. Improving clinical proficiency using a 3-dimensionally printed and patient-specific thoracic spine model as a haptic task trainer. *Reg Anesth Pain Med*. 2018;43(8):819-824. doi:10.1097/AAP.0000000000000821
36. Ventola CL. Medical applications for 3D printing: current and projected uses. *P T*. 2014;39(10):704-711.
37. Jeganathan J, Baribeau Y, Bortman J, et al. Use of 3-dimensional printing to create patient-specific thoracic spine models as task trainers. *Reg Anesth Pain Med*. 2017;42(4):469-474. doi:10.1097/AAP.0000000000000580
38. Filippou V, Tsoumpas C. Recent advances on the development of phantoms using 3D printing for imaging with CT, MRI, PET, SPECT, and ultrasound. *Medical physics*. 2018;45(9):e740-e760. doi:10.1002/mp.13058
39. Biglino G, Capelli C, Wray J, et al. 3D-manufactured patient-specific models of congenital heart defects for communication in clinical practice: feasibility and acceptability. *BMJ Open*. 2015;5(4):e007165. doi:10.1136/bmjopen-2014-007165
40. Kong X, Nie L, Zhang H, et al. Do 3D printing models improve anatomical teaching about hepatic segments to medical students? A randomized controlled study. *World journal of surgery*. 2016;40(8):1969-1976. doi:10.1007/s00268-016-3541-y

41. Evans LV, Dodge KL, Shah TD, et al. Simulation training in central venous catheter insertion: improved performance in clinical practice. *Acad Med*. 2010;85(9):1462-1469. doi:10.1097/ACM.0b013e3181eac9a3
42. Nikitichev DI, Barburas A, McPherson K, Mari J-M, West SJ, Desjardins AE. Construction of 3-dimensional printed ultrasound phantoms with wall-less vessels. *J Ultrasound Med*. 2016;35(6):1333-1339. doi:10.7863/ultra.15.06012
43. Ceh J, Youd T, Mastrovich Z, et al. Bismuth infusion of ABS enables additive manufacturing of complex radiological phantoms and shielding equipment. *Sensors (Basel)*. 2017;17(3):459. doi:10.3390/s17030459
44. Zeiler FA, Unger B, Kramer AH, Kirkpatrick AW, Gillman LM. A unique model for ultrasound assessment of optic nerve sheath diameter. *Can J Neurol Sci*. 2013;40(2):225-229. doi:10.1017/s0317167100013779
45. Turney BW. A new model with an anatomically accurate human renal collecting system for training in fluoroscopy-guided percutaneous nephrolithotomy access. *J Endourol*. 2014;28(3):360-363. doi:10.1089/end.2013.0616
46. Bogduk N. International Spinal Injection Society guidelines for the performance of spinal injection procedures: part 1: zygapophysial joint blocks. *Clin J Pain*. 1997;13(4):285-302. doi:10.1097/0002508-199712000-00003
47. Turker G, Kaya FN, Gurbet A, Aksu H, Erdogan C, Atlas A. Internal jugular vein cannulation: an ultrasound-guided technique versus a landmark-guided technique. *Clinics(Sao Paulo)*. 2009;64(10):989-992. doi:10.1590/S1807-59322009001000009
48. Akaike M, Fukutomi M, Nagamune M, et al. Simulation-based medical education in clinical skills laboratory. *J Med Invest*. 2012;59(1-2):28-35. doi:10.2152/jmi.59.28
49. Barsuk JH, McGaghie WC, Cohen ER, O'Leary KJ, Wayne DB. Simulation-based mastery learning reduces complications during central venous catheter insertion in a medical intensive care unit. *Crit Care Med*. 2009;37(10):2697-2701.
50. Lewiss RE, Hoffmann B, Beaulieu Y, Phelan MB. Point-of-care ultrasound education: the increasing role of simulation and multimedia resources. *J Ultrasound Med*. 2014;33(1):27-32. doi:10.7863/ultra.33.1.27
51. Makeeva V, Gullett JP, Dowla S, Olson K, Resuehr D. Evaluation of homemade ballistic gelatin phantoms as a low-cost alternative to commercial-grade phantoms in medical education. *Med Sci Educ*. 2016;26(3):307-316.
52. Mercaldi CJ, Lanes SF. Ultrasound guidance decreases complications and improves the cost of care among patients undergoing thoracentesis and paracentesis. *Chest*. 2013;143(2):532-538. doi:10.1378/chest.12-0447
53. Chung GKWK, Gyllenhammer RG, Baker EL. *The Effects of Practicing With a Virtual Ultrasound Trainer on FAST Window Identification, Acquisition, and Diagnosis*. Los Angeles, CA: National Center for Research on Evaluation, Standards, and Student Testing; 2011.
54. Kopacz DJ, Neal JM, Pollock JE. The regional anesthesia "learning curve": what is the minimum number of epidural and spinal blocks to reach consistency? *Reg Anesth*. 1996;21(3):182-190.
55. Smith MP, Sprung J, Zura A, Mascha E, Tetzlaff JE. A survey of exposure to regional anesthesia techniques in American anesthesia residency training programs. *Reg Anesth Pain Med*. 1999;24(1):11-16. doi:10.1016/s1098-7339(99)90159-1
56. Friedman Z, Siddiqui N, Katznelson R, Devito I, Bould MD, Naik V. Clinical impact of epidural anesthesia simulation on short-and long-term learning curve: high-versus low-fidelity model training. *Reg Anesth Pain Med*. 2009;34(3):229-232. doi:10.1097/AAP.0b013e3181a34345
57. Friedman Z, Siddiqui N, Katznelson R, Devito I, Davies S. Experience is not enough: repeated breaches in epidural anesthesia aseptic technique by novice operators despite improved skill. *Anesthesiology*. 2008;108(5):914-920. doi:10.1097/ALN.0b013e31816b6db6
58. Konrad C, Schupfer G, Wietlisbach M, Gerber H. Learning manual skills in anesthesiology: is there a recommended number of cases for anesthetic procedures? *Anesth Analg*. 1998;86(3):635-639. doi:10.1097/00000539-199803000-00037
59. Kunkler K. The role of medical simulation: an overview. *Int J Med Robot*. 2006;2(3):203-210.

© 2020 American Osteopathic Association