Development of an Ultrasound Phantom for Spinal Injections With 3-Dimensional Printing

Simeon J. West, FRCA, Jean-Martial Mari, PhD,* Azalea Khan, BSc,* Jordan H. Y. Wan, BSc,* Wenjie Zhu, BSc,* Ioannis G. Koutsakos, BSc,* Matthew Rowe, PhD,* Damon Kamming, FRCA,† and Adrien E. Desjardins, PhD**

Background and Objectives: This report describes a method for producing anatomically detailed, low-cost ultrasound phantoms of the spine with 3-dimensional printing. An implementation that involves representing a portion of the lumbar spine and the ligamentum flavum with 2 different printing materials and the surrounding soft tissues with agar gel is presented.
Methods: A computed tomography image volume of a patient with normal spinal anatomy was segmented to isolate the spine. Segments representing the ligamentum flavum and a supporting pedestal were digitally added, and the result was printed with a 3-dimensional printer. The printed spine was embedded in agar gel as a soft tissue component. Ultrasound images of the phantom were acquired and compared with those acquired from a human patient.
Results: The sonographic appearances of the phantom compared favorably with those observed from the human patient. The soft tissue component was suitable for needle insertions and could be remade replacing the agar.
Conclusions: Ultrasound phantoms that are derived directly from patient anatomy have strong potential as learning tools for ultrasound-guided spinal insertions, and they could be used as preprocedural planning tools in cases involving pathologies, implants, or abnormal anatomies. Three-dimensional printing is a promising method for producing low-cost phantoms with designs that can be readily shared across clinical institutions.

(*Reg Anesth Pain Med* 2014;39: 00–00)

Ultrasound imaging is widely used to guide needle insertions in regional anesthesia and interventional pain management. It is increasingly being used to guide needle insertions in the spinal region such as central neuraxial and paravertebral blocks,[1–3] particularly in patients with complex anatomies.[4,5] In a recent review by Kirkham and Chin,[6] the use of ultrasound is said to reduce the number of needle insertions and redirections, minimize the risk of traumatic needle placements, and improve block effectiveness after epidural placement. However, interpreting ultrasound images and maintaining visibility of the needle tip can be challenging, particularly for trainees.[7,8]

Imaging phantoms have been shown to be valuable training tools for improving visual-spatial awareness in ultrasound-guided procedures,[9,10] and several have been constructed for training in spinal ultrasound. For example, a simple imaging phantom was constructed by placing an anatomical spinal model in a water bath.[11] The use of an aqueous gel such as gelatin or agar can improve tactile needle feedback, relative to the use of plain water.[12,13] Commercially available ultrasound phantoms, which tend to be constructed from nonaqueous materials, provide tactile feedback that is similar to that encountered in clinical practice,[14] but they are typically based on generic models of sonoanatomy, they are expensive, and they have limited lifetimes because of the formation of needle tracks in the tissue-mimicking materials.

Three-dimensional (3D) printing, which is also known as "additive manufacturing," has the potential to transform how ultrasound phantoms are developed. It is now widely available in both academic and commercial institutions, and newer printers can generate objects with multiple materials that have different mechanical and ultrasonic properties. With custom or commercial software, standard image volumes such as those in DICOM format can readily be converted to printable files. This process has been used in other aspects of medicine, such as the production of custom implants for hip surgery[15] and dentistry.[16]

In this report, 3D printing was used to generate a model of the lumbar spine with detailed patient anatomy, which was derived from a computed tomography (CT) image volume. The use of 2 different materials to represent osseous and ligamentous structures was explored.

METHODS

The spinal model was generated from an anonymized CT image volume that was acquired as part of standard clinical practice from a patient with no apparent spinal pathology. Using a commercial software program (Mimics; Materialise, Leuven, Belgium), the image volume was segmented to isolate osseous structures in the lumbar region of L1-4, and image processing was performed to smoothen the segmented surface. A 3D printing file in a standard computer-aided design and manufacturing format (STL) was generated from the segmentation output using the same program.

A brief pilot study was performed to assess the mechanical and sonographic properties of printer materials. Four wedges were printed from different materials; each wedge was rectangular (length: 5 cm; width: 1 cm) with a thickness that tapered along the longitudinal axis from 2 mm to 0.1 mm. The first wedge was printed from the hard, translucent material DM8510; the other

From the *University College London and †University College Hospital, London, United Kingdom.
Accepted for publication June 19, 2014.
Address correspondence to: Simeon J. West, FRCA, Main Theatres, Maple Bridge Link Corridor, Podium 3, University College Hospital, 235 Euston Rd, London, United Kingdom NW1 2BU (e-mail: simeon.west@nhs.net).
Attribution: Department of Medical Physics and Bioengineering, University College London.
This study received funding from 2 student summer grants and incorporates the work of 4 BSc students, who made substantial contributions as part of their BSc projects at University College London. A.K. was granted £1520 toward subsistence by the Wellcome Trust and J.H.Y.W. was granted £2000 toward subsistence from the Institute of Making at the University College London. In addition, funding from the Department of Medical Physics and Bioengineering at University College London was used for 3-dimensional printing costs.
This study was presented orally at the European Society for Regional Anaesthesia 2013 Meeting in Glasgow. The presentation was entitled "Development of a Phantom for Ultrasound Guided Spinal and Epidural Anaesthesia With Three-Dimensional Polymer Printing."
The authors declare no conflict of interest.
Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.rapm.org).

ISSN: 1098-7339
DOI: 10.1097/AAP.0000000000000136

3 wedges were printed from rubbery materials DM9850 (softest), DM9870, and DM9885 (hardest), respectively.[17] These wedges were placed in water and visualized with ultrasound imaging; their appearances were compared qualitatively with ultrasound images of the ligamentum flavum acquired from human patients. In addition, the ability to puncture these wedges with spinal needles was assessed and compared with tactile feedback typically encountered in clinical experience. Based on this pilot study, the materials DM9885 and DM8510 were chosen to represent the ligamentum flavum and the osseous structures, respectively. From the assessment of the wedge, the DM9885 had optimum visibility and mechanical strength when its width was 0.8 mm.

As the ligamentum flavum was absent in the segmentation output, representative structures were manually drawn using an open-source 3D drawing software program (Blender; Stichting Blender Foundation, Amsterdam, the Netherlands). These structures had a width of 0.8 mm, and they were slightly curved outward toward the dorsal side. They were stored in a separate 3D printing file to allow them to be printed in a different material than that of the spinal model. The same program was also used to add a pedestal to the anterior surface of the vertebral body. This pedestal, which comprised a solid cylinder (diameter: 4 mm) and a rectangular base plate (length: 80 mm; width: 50 mm; thickness: 3 mm), allowed for the spinal model to be readily secured to the base of a container, ensuring that the spinal component remained in the correct orientation relative to the surface of the phantom (Figs. 1A, B). The pedestal was also saved as a separate 3D printing file to allow for changes in the orientation of the spinal model to be readily made in the future.

The spinal model, including the ligamentous structures and the pedestal, were printed at DMC London (The Bartlett School of Architecture, University College London). The printer (Objet 350 Connex; Stratasys, Minneapolis, Minnesota) allowed for the use of printing materials with different mechanical properties.

After printing, the spinal model was washed, and the rectangular plate was secured to a microwave-safe rectangular container with single-sided tape (Pro-POWER Gaffer tape; Premier Farnell, Leeds, UK). An agar solution comprising water and 5% agar (A7002; Sigma-Aldrich, St. Louis, Missouri) by weight was heated to 85°C, which is beyond its melting point.[18] Subsequently, this solution was manually mixed vigorously, degassed for 30 minutes, and then cooled down to 47°C. The latter temperature was above the gelling point of agar[19] but below the melting points of the printing materials. The container was filled with the partially gelled agar. During filling, the container was closed and slowly inverted a number of times to ensure filling of the hollow model and the release of trapped air bubbles. The ultrasound phantom was set in the refrigerator for 24 hours prior to use.

The total cost of the materials used to create the phantom was £533.40, of which the most significant cost was £500 (US $820) for the 3D printing. The other costs included £27.40 (US $45) for the agar and £6 (US $10) for the plastic container.

Ultrasound imaging was performed using a commercial system (S Nerve; FUJIFILM Sonosite Ltd, London, UK) with a 2- to 5-MHz curvilinear imaging probe (Sonosite C60n), at the Department of Medical Physics at the University College London. Images from the volunteer were compared with those of the phantom, with particular emphasis on the identification of anatomical structures relevant to ultrasound-guided spinal procedures. A 22-gauge, nonechogenic spinal needle (SN*2270; Terumo, Somerset, New Jersey) was inserted in plane under ultrasound guidance with both transverse and parasagittal oblique imaging probe

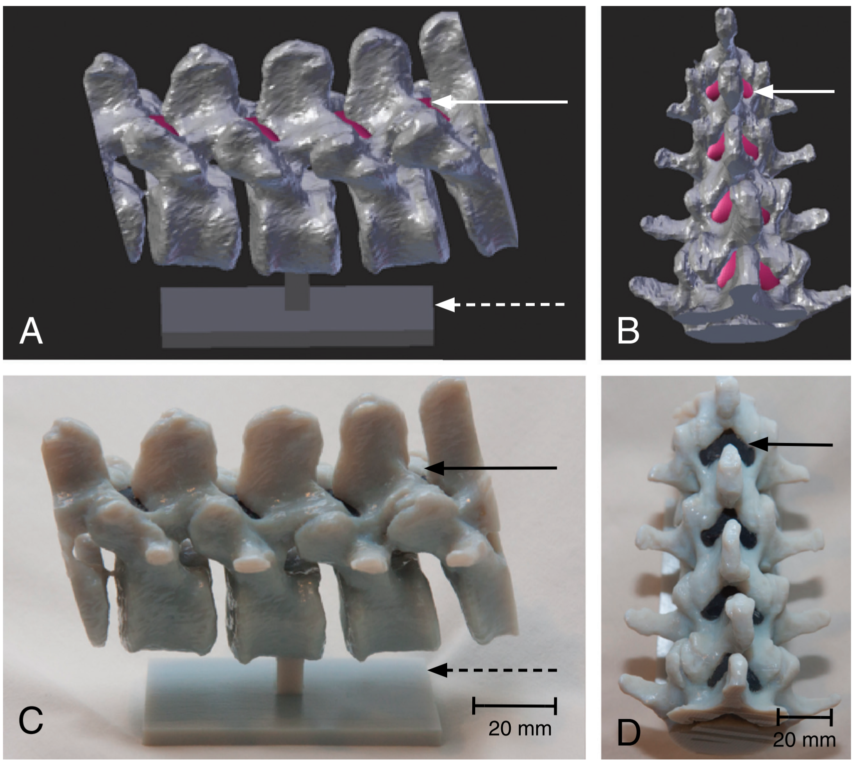

FIGURE 1. Digital model of the printed phantom, as visualized from the side (A) and from above (B). This model comprised osseous structures (gray), the ligamentum flavum (solid arrow), and the pedestal (dashed arrow). In the corresponding printed model (C, D), the osseous structures and the stand (dashed arrow) were gray; the ligamentum flavum (solid arrow) was black.

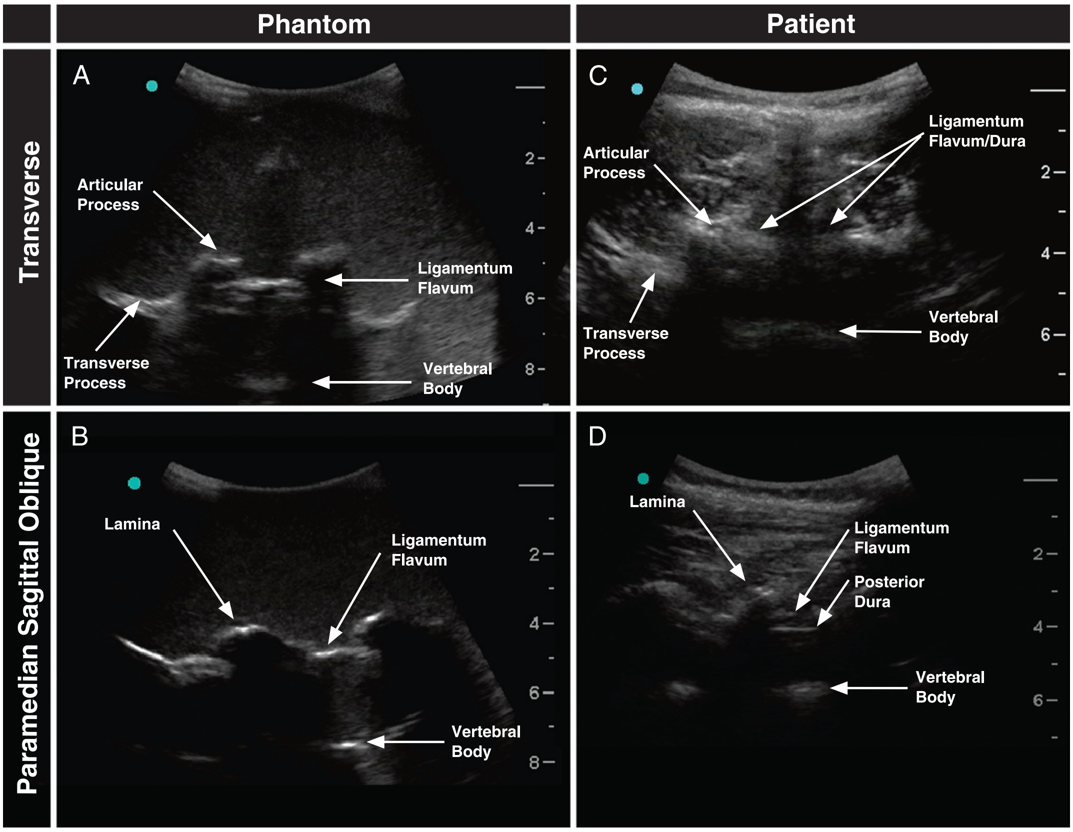

FIGURE 2. Ultrasound images of the imaging phantom with transverse (A) and paramedian sagittal oblique (B) views and the corresponding images of the lumbar spine of a healthy volunteer (C, D).

positions. Multiple punctures were performed, and each one culminated in the puncture of the ligamentum flavum.

RESULTS

The 3D printed spinal model was mechanically robust and had the same dimensions as those in the corresponding CT image volume (Figs. 1C, D). The spinous processes, the lamina, the ligamentum flavum, the transverse processes, and the vertebral bodies were all clearly visible (Figs. 2A, B). The component of the model representative of the ligamentum flavum was sufficiently transmissive to ultrasound so that the underlying vertebral bodies were visible. Both the osseous and the ligamentum components of the model had sonographic appearances similar to those of human patients (Figs. 2C, D). The ligamentum flavum in particular was more hyperechoic than similar clinical images and was visible spanning the interlamina space.

The agar surrounding the 3D printed spinal model had a homogenous, speckled appearance. A few air bubbles were present, which caused minor acoustic shadowing in the agar alone. The resistance to needle insertion through the ligamentum flavum components was perceptibly larger than that encountered in clinical practice, with more force required to penetrate. This led to a more positive end point in penetrating the ligamentum flavum than encountered clinically. The needle was visible on ultrasound in agar at angles of up to 50 degrees; however, needle tracks from previous attempts were seen (Fig. 3).

After ultrasound imaging and needle insertions, the 3D printed model was readily removed from the agar. Aside from the needle punctures to the ligamentum flavum components, no permanent changes to the model were observed.

DISCUSSION

Imaging phantoms are essential training tools for developing the skills to efficiently interpret ultrasound images and to maintain needle visibility.[9] In addition to the educational value that they provide to inexperienced practitioners, they also could be used

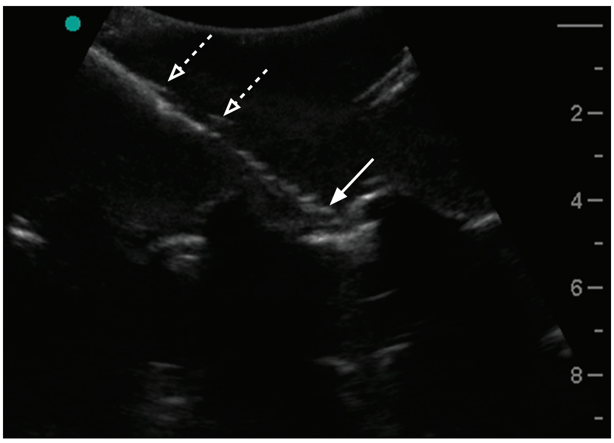

FIGURE 3. Paramedian sagittal oblique view of phantom with a 22-gauge needle inserted (solid arrow). Previous needle tracks are apparent in the top left of the image (dashed arrows).

by experienced practitioners to plan procedures on patients with abnormal anatomies. There is a need for new methods to create phantoms that are anatomically realistic, patient-specific, reusable, and low cost. This study is a step forward in that direction, and to the authors' knowledge, it was the first in which 3D printing was used to represent spinal anatomy.

The ultrasound phantom presented in this study had several limitations. First, the lack of variability in soft tissue structures posterior to the spine such as fat, muscle, and fascia limited its realism. In particular, the presumed lack of signal attenuation with an absent interspinous ligament may have contributed to a more hyperechoic and easily visible ligamentum flavum. In future phantoms, heterogeneities in the soft tissue regions could be created with layers of gel that have different ultrasonic properties. Second, the agar gel provided limited haptic feedback during needle insertions, and it has a limited shelf life. Both of these limitations of the agar gel could be addressed with use of nonorganic tissue-mimicking materials such as PVA[20] or Plastisol,[21] but those materials may not have the properties of agar gel that allow for needle tracks to be removed by melting in a microwave.[12]

Third, placing a spinal needle through the printed ligamentum flavum involved more resistance than is normally encountered clinically. This resistance was also slightly larger than that encountered with the initial tests conducted on the wedges. Further testing is required to test the acoustic and mechanical properties of printed materials.

With current software, significant experience with 3D drawing skills is required to add ligaments and a stand to a spinal structure. However, as medical image processing software improves, the image processing steps performed in this study may be within reach of most clinicians. Both the 3D printing files for imaging phantoms and the expertise with modifying these files are readily shared online. The 3D printing files to remake this model are available in an STL format at Supplemental Digital Content 1, http://links.lww.com/AAP/A117.

The process of using volumetric images of patients to generate ultrasound phantoms could be applied to create a wide range of phantoms that represent many different anatomical regions. In particular, the method presented in this study could be used to create phantoms of thoracic and cervical regions of the spine and of pediatric spines. As more materials for printing become available, it may be possible to print materials that have ultrasonic properties that are very similar to those of different soft tissue structures.

The ultrasound phantom in this study had a material cost that compared favorably to the prices of commercial ultrasound phantoms. With the former phantom, there is no limit on the number of needle insertions because the agar can be renewed to remove needle tracks. However, the ligamentum flavum structures cannot be renewed in the same way; thus, there are a finite number of punctures that can be performed. The costs of 3D printing and image segmentation software will surely decrease as these technologies become more pervasive. The printing files that image segmentation programs produce can be shared without restriction, and they can be edited with open source software programs. Open source alternatives to the commercial segmentation software that was used in this study are available.[22]

Volumetric images of patients could also be used to develop customized ultrasound training phantoms that accurately reproduce pathologies. For instance, a patient with severe scoliosis who requires an epidural procedure could have an ultrasound phantom created from a preprocedural CT image volume if it is available. These types of patient-specific phantoms could be used by practitioners to gain familiarity with the sonographic appearances of individual patients prior to the procedures. As such, they might ultimately allow for more spinal procedures to be performed with ultrasound guidance in place of conventional fluoroscopy, which would be beneficial from the standpoints of assisting needle placement and reducing radiation exposure.

In this study, a new method for producing low-cost spinal ultrasound phantoms with realistic representations of osseous structures and the ligamentum flavum was developed. The use of 3D printing to reproduce anatomical features that were segmented from preprocedural image volumes could ultimately be used to create a wide range of phantoms for training in regional anesthesia and interventional pain management.

REFERENCES

1. Shaikh F, Brzezinski J, Alexander S, et al. Ultrasound imaging for lumbar punctures and epidural catheterisations: systematic review and meta-analysis. *BMJ*. 2013;346:f1720–f1731.
2. Loizides A, Peer S, Plaikner M, et al. Ultrasound-guided injections in the lumbar spine. *Med Ultrason*. 2011;13:54–58.
3. Chin KJ, Karmakar MK, Peng P. Ultrasonography of the adult thoracic and lumbar spine for central neuraxial blockade. *Anesthesiology*. 2011;114: 1459–1485.
4. Chin KJ, Perlas A, Chan V, Brown-Shreves D, Koshkin A, Vaishnav V. Ultrasound imaging facilitates spinal anesthesia in adults with difficult surface anatomic landmarks. *Anesthesiology*. 2011;115:94–101.
5. Bowens C, Dobie KH, Devin CJ, Corey JM. An approach to neuraxial anaesthesia for the severely scoliotic spine. *Br J Anaesth*. 2013;111: 807–811.
6. Kirkham KR, Chin KJ. Ultrasound for Central Neuraxial Blockade. *Curr Anesthesiol Rep*. 2013;3:242–249.
7. Sites BD, Spence BC, Gallagher JD, Wiley CW, Bertrand ML, Blike GT. Characterizing novice behavior associated with learning ultrasound-guided peripheral regional anesthesia. *Reg Anesth Pain Med*. 2007;32:107–115.
8. Margarido CB, Arzola C, Balki M, Carvalho JC. Anesthesiologists' learning curves for ultrasound assessment of the lumbar spine. *Can J Anaesth*. 2010;57:120–126.
9. Hocking G, Hebard S, Mitchell CH. A review of the benefits and pitfalls of phantoms in ultrasound-guided regional anesthesia. *Reg Anesth Pain Med*. 2011;36:162–170.
10. Nix CM, Margarido CB, Awad IT, et al. A scoping review of the evidence for teaching ultrasound-guided regional anesthesia. *Reg Anesth Pain Med*. 2013;38:471–480.
11. Greher M, Scharbert G, Kamolz LP, et al. Ultrasound-guided lumbar facet nerve block: a sonoanatomic study of a new methodologic approach. *Anesthesiology*. 2004;100:1242–1248.
12. Bellingham GA, Peng PW. A low-cost ultrasound phantom of the lumbosacral spine. *Reg Anesth Pain Med*. 2010;35:290–293.
13. Li JW, Karmakar MK, Li X, Kwok WH, Ngan Kee WD. Gelatin-agar lumbosacral spine phantom: a simple model for learning the basic skills required to perform real-time sonographically guided central neuraxial blocks. *J Ultrasound Med*. 2011;30:263–272.
14. Rosenberg AD, Popovic J, Albert DB, et al. Three partial-task simulators for teaching ultrasound-guided regional anesthesia. *Reg Anesth Pain Med*. 2012;37:106–110.
15. Rahmati S, Abbaszadeh F, Farahmand F. An improved methodology for design of custom-made hip prostheses to be fabricated using additive manufacturing technologies. *Rapid Prototyping J*. 2012;18: 389–400.
16. Bartolo P, Kruth J-P, Silva J, et al. Biomedical production of implants by additive electro-chemical and physical processes. *CIRP Ann Manuf Technol*. 2012;61:635–655.

17. Stratasys Web site. Digital Materials Data Sheet. Available at: http://www.stratasys.com/~/media/Main/Secure/Material%20Specs%20MS/PolyJet-Material-Specs/Digital_Materials_Datasheet.ashx. Accessed November 19, 2013.
18. Burlew MM, Madsen EL, Zagzebski JA, Banjavic RA, Sum SW. A new ultrasound tissue-equivalent material. *Radiology.* 1980;134:517–520.
19. Sigmaaldrich Web site. Available at: http://www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Sigma-Aldrich/Product_Information_Sheet/a7002pis.pdf. Accessed November 19, 2013.
20. Culjat MO, Goldenberg D, Tewari P, Singh RS. A review of tissue substitutes for ultrasound imaging. *Ultrasound Med Biol*. 2010;36:861–873.
21. Lerman IR, Souzdalnitski D, Narouze S. A low-cost, durable, combined ultrasound and fluoroscopic phantom for cervical transforaminal injections. *Reg Anesth Pain Med*. 2012;37:344–348.
22. Frame M, Huntley JS. Rapid prototyping in orthopaedic surgery: a user's guide [published online ahead of print May 1, 2012]. *Sci World J*. 2012;838575.