Gelatin-Agar Lumbosacral Spine Phantom

A Simple Model for Learning the Basic Skills Required to Perform Real-time Sonographically Guided Central Neuraxial Blocks

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This report describes the preparation of a gelatin-agar spine phantom that was used for spinal sonography and to practice the hand-eye coordination skills required to perform sonographically guided central neuraxial blocks. The phantom was prepared by embedding a lumbosacral spine model into a mixture of gelatin and agar in a plastic box. Cellulose powder and chlorhexidine were also added to the mixture, after which it was allowed to solidify. Sonography of the osseous elements of the lumbosacral spine in the phantom was then performed, and their sonographic appearances were compared to those in volunteers. Simulated real-time sonographically guided paramedian spinal needle insertions were also performed in the phantom. The texture and echogenicity of the phantom were subjectively comparable to those of tissue in vivo. The osseous elements of the spine in the phantom were clearly delineated, and their sonographic appearances were comparable to those seen in vivo in the volunteers. During the simulated sonographically guided spinal injections, the needle could be clearly visualized, but the phantom provided little tactile feedback. In conclusion, the gelatin-agar spine phantom is a simple and inexpensive sonographic spine model that has a tissuelike texture and echogenicity. It can be used to study the osseous anatomy of the lumbar spine and practice the skills required to perform sonographically guided central neuraxial blocks.

Key Words—agar; central neuraxial blocks; gelatin; phantom; sonography; spine

Recently there has been an increase in interest among anesthesiologists and pain physicians in acquiring the skills necessary to perform spinal sonography and sonographically guided central neuraxial blocks (spinal and epidural).[1] These techniques require advanced interventional skills, and competence is acquired with experience and training. Today there are few models for learning spinal sonography or sonographically guided central neuraxial blocks. The water-based spine phantom is useful for learning the osseous anatomy of the spine,[1,2] and human volunteers are used for learning spinal sonography. However, volunteers are not suitable for practicing sonographically guided central neuraxial blocks, and practicing such delicate interventions in patients may not be ethically justifiable. Courses using fresh cadavers allow participants to study the neuraxial sonographic anatomy and practice sonographically guided central neuraxial blocks with realistic tactile feedback, but they are often limited by the quality of the sonograms. Moreover, such courses are rare, are usually conducted in anatomy departments, and can be expensive. Therefore, an in vitro model that can facilitate learning of the scanning techniques and hand-eye coordination skills required for real-time sonographically guided central neuraxial blocks is desirable.

A gelatin-based sonographic phantom of the lumbosacral spine has recently been described.[3] However, the gelatin phantom is soft in consistency, lacks tissue-mimicking echogenic properties, and provides no tactile feedback, and needle track marks are a problem,[3] which precludes its extended use. In addition, this phantom has a short use life.[3] In this report, we describe the preparation of a gelatin-agar spine phantom and discuss the advantages and disadvantages of this phantom as a model for learning the basic skills required to perform spinal sonography and sonographically guided central neuraxial blocks.

Materials and Methods

The gelatin-agar spine phantom was prepared by embedding a lumbosacral spine model (L1 to the sacrum; Sawbones; Pacific Research Laboratories, Inc, Vashon, WA) into a mixture of gelatin and agar. The spine model used (Figure 1A) was articulated and contained artificial material that mimicked the ligamentum flavum and the anterior and posterior longitudinal ligaments but not the neuraxial structures (dura and cauda equina nerves). The spine model was secured to the base of a plastic box (length × width × height, 32 × 22 × 20 cm) using Blu-Tack (Bostik Pty, Ltd, Thomastown, Victoria, Australia), which is a puttylike adhesive, such that its spinous processes were facing the ceiling (Figure 1A). The volume of gelatin and agar required to immerse the spine model such that 1 to 2 cm of the mixture was above the tip of the spinous processes was then determined using tap water and was approximately 8 L in this model. A depth of 1 to 2 cm from the skin to the spinous processes was chosen to mimic the typical depth in humans.

The ingredients used to prepare the gelatin-agar mixture were 5.5% dry weight gelatin powder (bovine skin type B; Sigma-Aldrich, St Louis, MO) and 1% dry weight agar powder (Sigma-Aldrich) in water. Sigmacell S5504 cellulose powder (type 50, 50-μm diameter, 0.25% by mass; Sigma-Aldrich) was also added to the mixture because Sigmacell particles cause scattering of the ultrasound signal and impart a tissuelike appearance to the sonograms.[4,5] Chlorhexidine (0.05% wt/vol, 1.25% by volume; Baxter Healthcare Pty, Ltd, Old Toongabbie, New South Wales, Australia) was also added to the mixture for its antibacterial properties.[6] The gelatin-agar mixture was prepared by dissolving 440 g of gelatin and 80 g of agar in 3560 and 3920 mL of water, respectively, to make up the predetermined volume of 8 L. The two solutions were prepared in separate glass containers, and their temperature was closely monitored (type K thermocouple, model 421501, Extech Instruments Corporation, Waltham, MA) because gelatin and agar have different melting points. The containers were heated, and the solutions were continuously stirred until the gelatin and agar had dissolved in the solution. The gelatin generally dissolved at 50°C to 60°C, whereas the agar dissolved at 93°C. The agar solution was allowed to cool below 50°C before it was mixed with the gelatin solution in a 1:1 volume ratio. Twenty grams of Sigmacell cellulose powder was then added to the mixture while the solution was continuously stirred to prevent gravitational sedimentation of the Sigmacell particles. When the temperature of the mixture reached 45°C, 100 mL of chlorhexidine, 0.05%, which is not flammable, was added for its antibacterial properties, and at 37°C, the now slightly thickened mixture was poured into the plastic box containing the spine model and allowed to harden at room temperature, after which it was stored in a refrigerator at 4°C until it was used.

Figure 1. Gelatin-agar spine phantom. **A**, Lumbosacral spine model secured to the base of the plastic box. **B**, Spine phantom after being embedded in the gelatin-agar mixture.
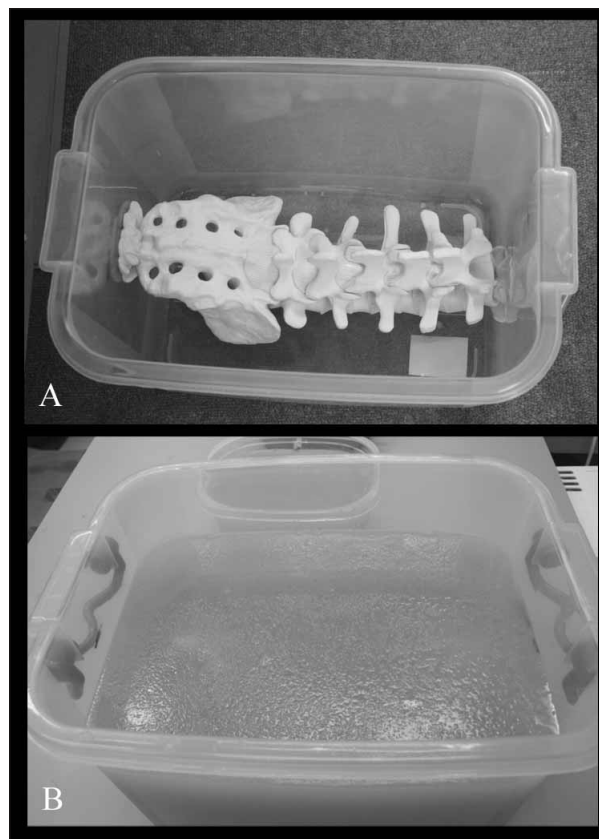
The gelatin-agar spine phantom was scanned using an HD11 XE ultrasound system (Philips Healthcare, Andover, MA) with still-image and video recording capabilities and a C9-4 curved array broadband transducer (operating frequency range, 9–4 MHz). The latter was chosen for the scan because the neuraxial structures are located at a considerable depth in vivo, and low-frequency ultrasound (5–2 or 9–4 MHz), which penetrates deeper into body tissue than high-frequency ultrasound, is best suited to imaging the spine. Moreover, the divergent beam from a curved array transducer also produces a wide field of view that is ideal when one performs real-time sonographically guided central neuraxial blocks. The following adjustments were made on the ultrasound system to optimize the images during the scan: (1) an appropriate depth setting was selected (6–13 cm); (2) the focus was adjusted to the appropriate depth; (3) the general (midrange) or penetration (low-frequency) range was selected; (4) SonoCT (compound imaging) was selected; and (5) the gain was adjusted manually to obtain the best possible image. A thin layer of water (2–3 mm deep) or ultrasound gel was used for acoustic coupling during the scan and while practicing the needle insertion technique. Sonography of the lumbosacral spine in the phantom was performed in the transverse and sagittal axes. The L3-L4 and L4-L5 intervertebral spaces were chosen as the targets for the sonographic scans and needle insertion in the gelatin-agar spine phantom because most central neuraxial interventions are performed through these interspaces in clinical practice.

The following scanning routine was followed. The sacrum was first identified on a sagittal scan as a flat hyperechoic structure with a large acoustic shadow anterior to it (Figure 2A). The gap between the sacrum and the L5 lamina was the L5-S1 gap (Figure 2A), and the L3-L4 and L4-L5 intervertebral spaces were then identified on a paramedian sagittal scan by counting the interlaminar spaces

Figure 2. Sagittal sonograms of the L5-S1 gap (**A** and **B**) and the spinous processes (**C** and **D**) from the gelatin-agar spine phantom (**A** and **C**) and volunteers (**B** and **D**). AC indicates anterior complex; ISS, interspinous space; ITS, intrathecal sac; SC, spinal canal; and SP, spinous processes.
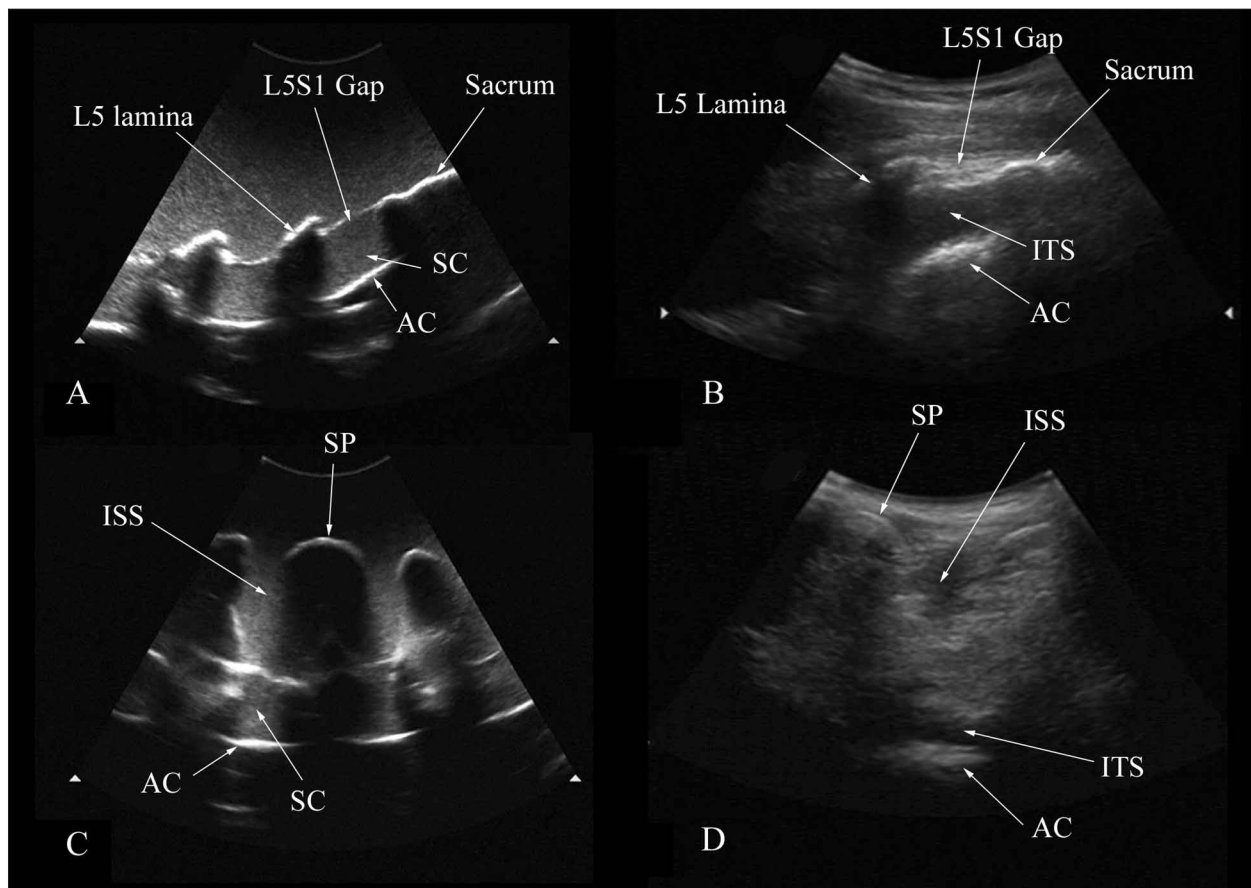
cranially. A sagittal scan was then performed in the midline over the spinous processes (Figure 2C) and laterally (paramedian) over the lamina (Figure 3A), articular processes of the facet joints (Figure 3D), and transverse processes (Figure 4A). Finally, a transverse scan was performed over the spinous processes (Figure 5A), through the interspinous space (interspinous scan; Figure 5C), and over the sacrum at the level of the sacral hiatus (Figure 4C).

After Research Ethics Committee (Joint Chinese University of Hong Kong–New Territories East Cluster Clinical Research Ethics Committee) approval and written informed consent were obtained, 2 healthy volunteers were recruited. Scans were performed on the volunteers according to the scanning routine described above. During the scans, the volunteers were positioned in the left lateral po-

sition with their hips and knees flexed as during a spinal or epidural injection. Representative still images (tagged image file format, 720 × 480 pixels and 8-bit gray levels) were captured from the video loops that were recorded during the scans using Premier Pro 2.0 (Adobe Systems, Inc, San Jose, CA), and the sonographic appearances of the osseous elements from the gelatin-agar spine phantom and volunteers were compared visually (Figures 2–5).

Real-time sonographically guided needle insertions, to mimic paramedian spinal injections, were then performed on the gelatin-agar spine phantom by the authors and members of their research group. The technique used for the spinal intervention was the same as what we have previously described for epidural injections.[7] A paramedian sagittal scan was performed over the L3-L4 and L4-L5

Figure 3. Paramedian sagittal sonograms of the lumbar spine at the L3-L4 and L4-L5 levels over the lamina (**A** and **B**) and articular processes of the facet joints (**C** and **D**) from the gelatin-agar spine phantom (**A** and **C**) and volunteers (**B** and **D**). A graphic overlay has been placed over the L4 lamina in **B** to illustrate the pattern resembling the head and neck of a horse, which we refer to as the "horse head sign," and an inset has been placed in **D** to illustrate the camel hump–like appearance of the articular processes, which we refer to as the "camel hump sign." AC indicates anterior complex; APFJ, articular processes of the facet joints; ES, epidural space; ESM, erector spinae muscle; ILS, interlaminar space; ITS, intrathecal sac; LF, ligamentum flavum; PD, posterior dura; and SC, spinal canal.
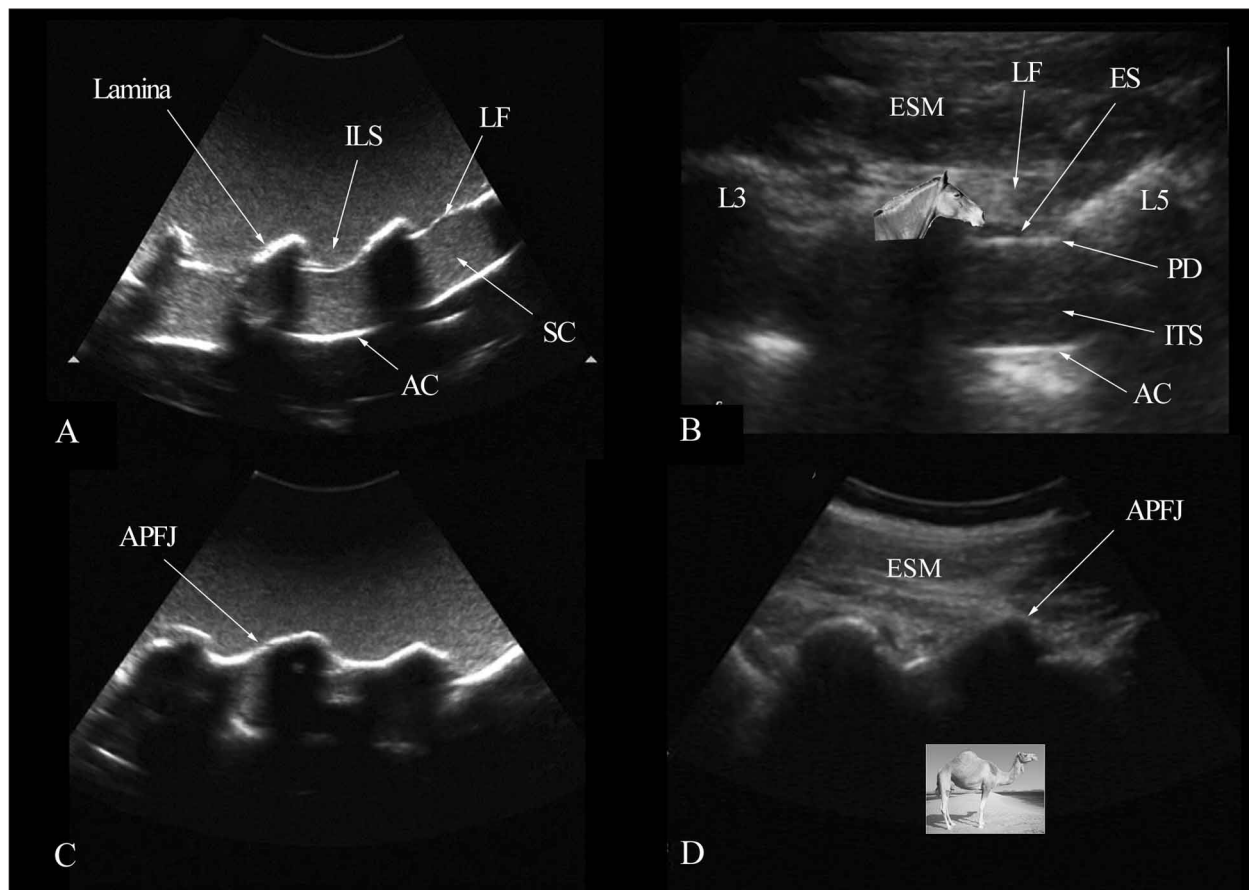
lamina (Figure 6A). The paramedian axis was chosen for the intervention because neuraxial structures are better visualized through the paramedian axis than through the median transverse or median sagittal axis.[8] During the scan, the transducer was also tilted slightly medially so that the incident beam was insonated in a paramedian oblique sagittal axis.[7] This was done to ensure that the ultrasound beam entered the spinal canal through the widest part of the interlaminar space. A 22-gauge Tuohy needle (8 cm; B. Braun Medical, Inc, Bethlehem, PA) with its stylet in situ was then inserted in the plane of the ultrasound beam (in-plane technique; Figure 6A) and advanced through the interlaminar space until it was seen to traverse the artificial ligamentum flavum and enter the spinal canal (Figure 6B). This is also the path a spinal or epidural needle takes during a paramedian spinal or epidural injection.[7,8]

Results

A simple gelatin-agar spine phantom was prepared. It took approximately 1 hour to prepare the phantom and 6 to 8 hours for the gelatin-agar mixture to solidify and harden in the box at room temperature (Figure 1B). The total cost for preparing the gelatin-agar spine phantom was approximately US$90, of which US$80 was spent to buy the spine model, which could be reused. The texture and echogenicity of the phantom were subjectively comparable to those of tissue in vivo.

The osseous elements of the spine in the phantom were clearly delineated on the sonograms. The spinous processes were identified as crescent- or semilunar- shaped hyperechoic structures with an acoustic shadow anteriorly (Figure 2C). The intervening areas between the adjoining

Figure 4. Sagittal sonograms of the transverse processes at the L3-L4 and L4-L5 levels (**A** and **B**) and transverse scans of the sacral hiatus (**C** and **D**) from the gelatin-agar spine phantom (**A** and **C**) and volunteers (**B** and **D**). Note how the acoustic shadow of the transverse processes produces a sonographic pattern that we refer to as the "trident sign." ESM indicates erector spinae muscle; PM, psoas muscle; SC, sacral cornua; SCM, sacrococcygeal membrane; and TP, transverse processes.
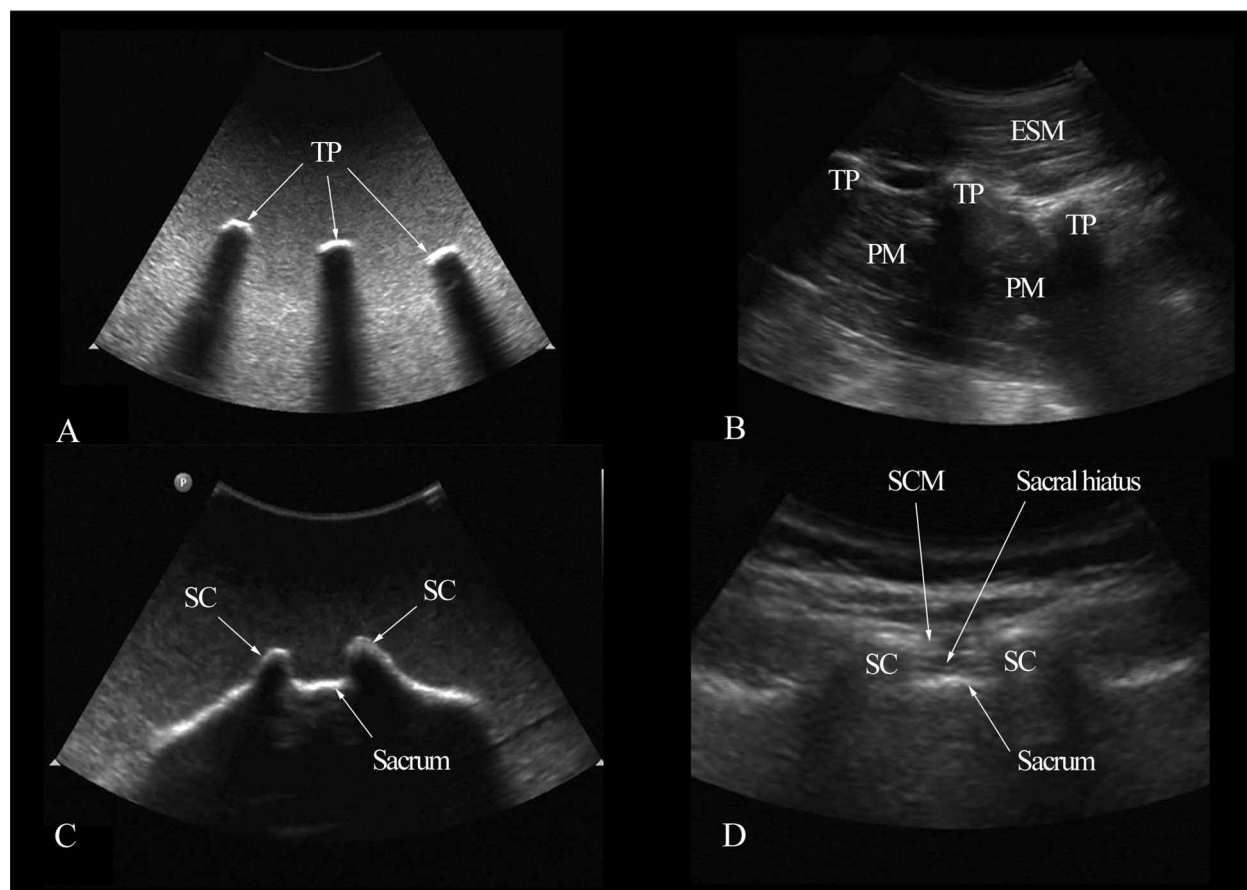
spinous processes were the interspinous spaces, and the hyperechoic reflections anteriorly were from the artificial ligamentum flavum and the anterior dura–posterior longitudinal ligament–vertebral body complex (anterior complex; Figure 2C).[1,7] The lamina also appeared hyperechoic and was the first osseous structure visualized on the paramedian sagittal scan (Figure 3A). Because bone impedes the passage of ultrasound, there was an acoustic shadow anterior to each lamina. The sonographic appearance of the lamina produced a pattern, resembling the head and neck of a horse, which we refer to as the "horse head sign" (Figure 3A).[1] A gap was also seen between adjoining lamina, which was the interlaminar space (Figure 3A). The articular processes of the facet joints were the next osseous structures visualized lateral to the lamina. They appeared as a continuous hyperechoic wavy line with no intervening gaps (Figure 3C) resembling multiple camel humps, which we refer to at the "camel hump sign." The trans-

verse processes were lateral to the articular processes of the facet joints and produced what we refer to as the "trident sign"[9] (Figure 4A). On a transverse sonogram, the spinous processes were seen as a hyperechoic reflection, anterior to which there was a dark acoustic shadow (Figure 5A) that completely obscured the spinal canal. On the transverse scan through the interspinous space (interspinous scan), because the ultrasound beam was not obstructed by the spinous processes, the transverse processes, articular processes of the facet joints, artificial ligamentum flavum, anterior complex, and spinal canal were visualized (Figure 5D). The sacral cornua were identified as two hyperechoic reversed U-shaped structures, one on either side of the midline (Figure 4C), at the level of the sacral hiatus. The sonographic appearance of the osseous elements of the spine in the gelatin-agar spine phantom was comparable to that seen in vivo in the volunteers (Figures 2–5).

Figure 5. Transverse sonograms of the spinous processes (**A** and **B**) and through the interspinous space (**C** and **D**) from the gelatin-agar spine phantom (**A** and **C**) and volunteers (**B** and **D**). AC indicates anterior complex; APFJ, articular processes of the facet joints; ITS, intrathecal space; LF, ligamentum flavum; PD, posterior dura; SC, spinal canal; SP, spinous processes; and TP, transverse processes.
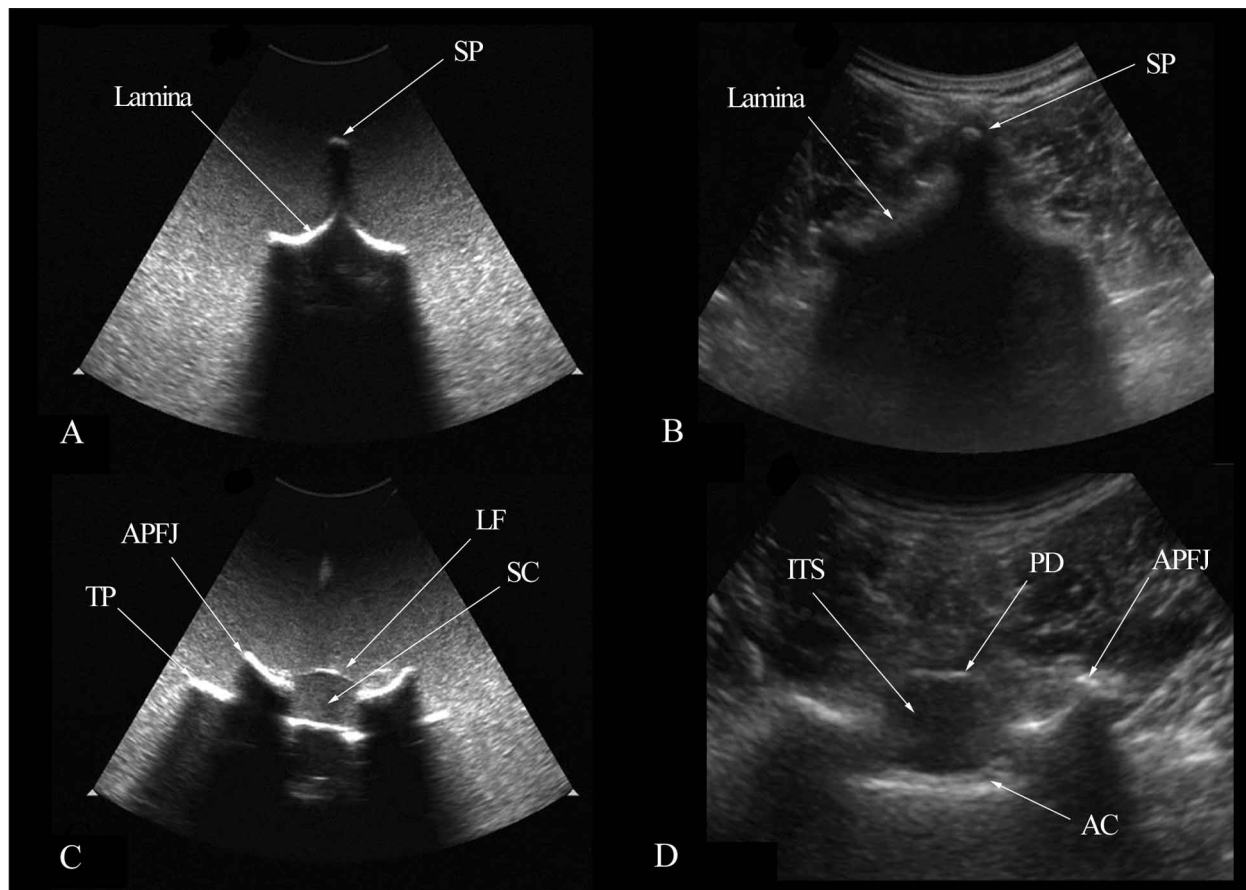
During the simulated spinal injections in the phantom, the needle could be clearly visualized (Figure 6B), but it provided little tactile feedback. Needle track marks were also present in the phantom after the needling, but it is our experience that they are less of a problem than with gelatin-based phantoms. We also find that the use of water as the coupling agent results in fewer needle track marks. The addition of chlorhexidine to the gelatin-agar mixture appears to retard the growth of bacteria and mold on the surface of the phantom. When stored at 4°C in a refrigerator, the gelatin-agar spine phantom could be used for nearly 4 months.

Discussion

In this report, we describe the preparation of a simple, low-cost gelatin-agar lumbosacral spine phantom. Subjectively, the texture and echogenicity of the phantom were comparable to those of tissue, and the sonographic appearances

Figure 6. Practice in-plane needle insertion in the gelatin-agar spine phantom (**A**) and corresponding sonogram (**B**). Note how the spinal needle is clearly visible and is seen to have entered the spinal canal through the interlaminar space. ILS indicates interlaminar space; and SC, spinal canal.
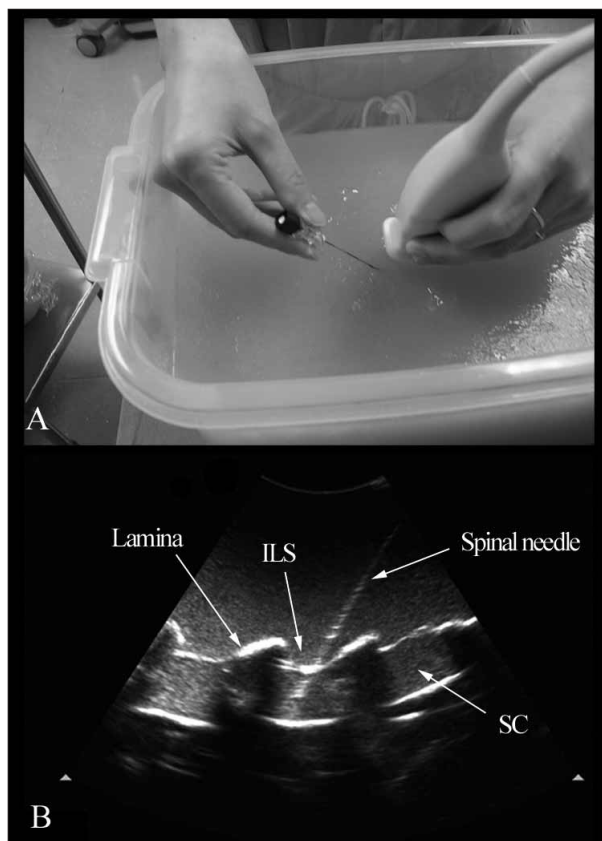
of the osseous elements of the spine in the phantom were also comparable to those seen in vivo. We were also able to practice the hand-eye coordination skills required to perform real-time sonographically guided central neuraxial blocks by simulating a paramedian spinal injection. We believe that this simple model may become a valuable tool for teaching and learning of sonographically guided central neuraxial blocks.

The advantages and disadvantages of the various spine phantoms are outlined in Table 1. The water-based spine phantom,[2] which is prepared by immersing a lumbosacral spine model in a water bath, is useful for learning the sonographic appearance of the osseous anatomy of the spine but is not a good model for learning sonographically guided spinal interventions because of a lack of tissue-mimicking structures. We have also been using anesthetized pigs to teach spinal sonography and sonographically guided central neuraxial blocks at workshops. Anesthetized pigs are useful, but they require animal ethics committee approval, and organizers are required to obtain a license from the local health department to conduct such workshops. They also pose a risk for the spread of porcine infections, and religious beliefs may preclude their use as models. Moreover, such workshops are usually conducted in designated animal laboratories, which are often small and unable to accommodate large groups of participants. To circumvent some of these problems, our group recently described a pig carcass spine phantom,[10] which is an excellent model, can be used in conference venues, and provides excellent tactile and visual feedback.[10] However because the pig carcass spine phantom is a decapitated model, there is a loss of cerebrospinal fluid during the slaughtering process. This often results in air artifacts and loss of contrast within the spinal canal during spinal sonography unless the thecal sac is cannulated at its cranial end and filled with fluid (normal saline), a process that requires surgical dissection to isolate the thecal sac. We have also used a commercially available lumbosacral spine model (model 034 lumbar training phantom; Computerized Imaging Reference Systems, Inc, Norfolk, VA) that is designed for fluoroscopically guided interventions but is also suitable for practicing sonographically guided central neuraxial blocks. However, it is our experience that this model is expensive (≈US$3700), and needling this phantom leaves needle track marks, which precludes extended use of this product.

A low-cost gelatin-based sonographic phantom of the lumbosacral spine has recently been described.[3] Although the gelatin phantom is transparent and provides excellent sonograms of the osseous elements of the lumbosacral

Table 1. Comparison of Spine Phantoms

Model	Advantages	Disadvantages
Fresh cadavers	Realistic spinal sonographic anatomy. Can be used to practice sonographically guided central neuraxial blocks. Provides realistic tactile feedback. Also provides visual feedback during needle insertion. Cost: ≈US$3000–5000 per cadaver.	Cadavers are difficult to obtain. Poor-quality sonograms. Cadaver courses are rare and expensive.
Anesthetized pigs	Good model for learning scanning techniques and spinal sonographic anatomy. Excellent model for practicing sonographically guided central neuraxial blocks. Provides realistic tactile and visual feedback Intrathecal needle placement readily confirmed by observing free flow of cerebrospinal fluid. Cost: US$800–1000 per pig for a half-day workshop session.	Requires animal ethics committee approval. Organizers of animal workshops also require a license from the local health department to perform animal experiments. Risk of contracting porcine infections. Religious beliefs may preclude the use of a pig model. Limited to designated animal laboratories or facilities, which can often accommodate only a small number of participants.
Pig carcass spine phantom	Can be procured directly from a local government approved abattoir. No ethical issues. Does not require a license to conduct sonographically guided spinal interventions (experiments). Can be used in conference venues with large numbers of participants. Excellent tactile and visual feedback. Intrathecal needle placement readily confirmed by observing free flow of cerebrospinal fluid (or saline, if the thecal sac is infused with saline). Cost: US$250 (includes delivery and disposal of the carcass).	Religious beliefs may preclude the use of a pig carcass model. Decapitation during the slaughtering process leads to a loss of cerebrospinal fluid, which produces air artifacts and loss of contrast within the spinal canal. Simple and inexpensive.
Water-based spine phantom	Requires very little time and effort to set up. The lumbosacral spine model immersed in the water bath does not deteriorate or decompose like animal tissue-based phantoms, so it can be reused over and over again. Useful tool for learning the sonographic appearance of the osseous elements of the spine. Cost: US$80.	Does not have any tissue-mimicking structures. Lacks tissue-mimicking echogenic properties (anechoic background). No tactile feedback during simulated needle insertion.
Computerized Imaging Reference Systems lumbar training phantom (model 034; Computerized Imaging Reference Systems, Inc, Norfolk, VA)	Commercially available. Tissue-mimicking echogenic properties. Provides tactile feedback during simulated needle insertion. Can also be used with fluoroscopy, computed tomography, and magnetic resonance imaging. Cost: US$3700.	Expensive. Needle track marks, which preclude extended use. Limited shelf life (6 mo).
Gelatin-based spine phantom	Low cost. The lumbosacral spine model embedded in the phantom can be reused. Useful for learning the sonographic appearance of the osseous elements of the spine. Can also be used to practice simulated sonographically guided spinal injections. Because gelatin is transparent, one is able to see the advancing needle during a simulated sonographically guided spinal injection. Cost: US$80.	Soft consistency and mechanically unstable. No tactile feedback during needle insertion. Needle track marks are a major problem. Mold and bacterial growth on the surface in <1 wk. Only 20 needle passes per phantom. Short use life: 3 wk, after which there is degradation of the gelatin.

(continued)

spine,[3] it is soft in consistency, lacks tissue-mimicking echogenic properties, and provides no tactile feedback, and needle track marks are a major problem.[3] Although the latter can be erased by melting the gelatin block in a microwave oven, allowing the phantom to be reused after it resolidifies, it can only be used for a limited number of attempts each time (≈20 attempts in the lumbar region).[3] Another drawback is the fact that these models become infiltrated with mold and bacteria in less than 1 week, and given the organic nature of gelatin, even additives such as boric acid are unable to prevent the infiltration (V. J. Patel, MD, St Luke's Roosevelt Hospital Center, New York, NY, e-mail communication, June 2010). All of these drawbacks make the gelatin-based spine phantom unsuitable for extended use.

The gelatin-agar spine phantom described in this report appears to overcome some of the drawbacks of the gelatin-based spine phantom. Although gelatin is soft and agar is firm in consistency,[11] combining the two, as in this study, makes the texture of the phantom mechanically stable[11] and has previously been used to prepare models for tissue sonoelastography.[11,12] The texture of the phantom can also be varied by changing the composition of gelatin and agar in the mixture.[12] By causing scattering of the incident ultrasound signal, the addition of Sigmacell particles to the gelatin-agar mixture also imparts a tissuelike appearance to the sonograms. The sonographic appearances of the osseous elements of the spine in the phantom

were also comparable to those seen in vivo, making it an excellent model for studying the osseous anatomy of the spine. The phantom is easy to prepare and considerably less expensive than most commercially available models, and it is our experience that needle track marks are less of a problem than with the gelatin-based spine phantom. As a result, we have been able to successfully use a single gelatin-agar spine phantom for scanning and needling practice at workshops with up to 200 participants. We have also observed that the use of a Tuohy stylet needle and water as the coupling agent while practicing the needling technique contributes to fewer needle track marks. This may be because less or no air is introduced into the phantom through the needle tracks. Moreover, unlike the gelatin-based spine phantom, which is transparent,[3] the gelatin-agar spine phantom is opaque, making it impossible to visualize the spine from the surface. Therefore one has to rely on imaging and hand-eye coordination skills to perform a simulated central neuraxial intervention similar to that performed in clinical practice. The addition of chlorhexidine to the gelatin-agar mixture appears to retard the growth of bacteria and mold on the surface of the phantom. When stored at 4°C in a refrigerator, we have been able to preserve the phantom for nearly 4 months before it becomes unusable, as indicated by an excessive growth of mold and bacteria on the surface of the phantom. This extended life span appears to be an additional benefit of this inexpensive sonographic spine model. Major limitations

Table 1. Comparison of Spine Phantoms (continued)

Model	Advantages	Disadvantages
Gelatin-agar spine phantom (this study)	Simple to prepare. Low cost. Mechanically stable. Tissue-mimicking echogenic properties (subjective assessment). Useful for learning the sonographic appearance of the osseous elements of the spine. Can be used to practice simulated sonographically guided spinal injection. Opaque in appearance, so it is a good model to practice hand-eye coordination skills required for sonographically guided central neuraxial blocks. Needle track marks are less of a problem than with a gelatin-only phantom (personal experience). Using a Tuohy stylet needle and saline as the coupling agent can contribute to fewer needle track marks during a simulated sonographically guided spinal injection. Longer use life than a gelatin-only phantom (4 mo). The lumbosacral spine model embedded in the phantom can be reused. Cost: US$90.	No neuraxial structures (dura, cauda equina nerves, and cerebrospinal fluid) in the phantom. No tactile feedback during needle insertion.

Advantages and disadvantages are shown for the various models and phantoms of the lumbosacral spine that are in use today for teaching and learning spinal sonography and practicing the hand-eye coordination skills required to perform sonographically guided central neuraxial blocks.

of the gelatin-agar spine phantom are that there are no neuraxial structures (dura, cauda equina nerves, and cerebrospinal fluid) in the phantom, and it does not provide tactile feedback during needle insertion.

In conclusion, the gelatin-agar spine phantom is a simple and inexpensive in vitro model that has a tissuelike texture and echogenicity and can be used over extended periods to study the osseous anatomy of the lumbosacral spine and practice the hand-eye coordination skills required to perform sonographically guided central neuraxial blocks. It is a valuable addition to the limited number of tools that are currently available for learning spinal sonography and sonographically guided central neuraxial blocks. Future research should look at incorporating artificial material in the phantom to mimic the dura, epidural space, and thecal sac so that it can also provide visual feedback while practicing simulated sonographically guided central neuraxial blocks. There is also the need to evaluate how this new tool may affect the learning curves for spinal sonography and sonographically guided central neuraxial blocks in novices. The gelatin-agar preparation described in this report may also be used to prepare sonographic phantoms of other parts of the body (pelvis and hip, shoulder joint, and foot and ankle), and future research in this area is warranted.

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