Creation of a High-fidelity, Low-cost Pediatric Skull Fracture Ultrasound Phantom

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Over the past decade, point-of-care ultrasound has become a common tool used for both procedures and diagnosis. Developing high-fidelity phantoms is critical for training in new and novel point-of-care ultrasound applications. Detecting skull fractures on ultrasound imaging in the younger-than-2-year-old patient is an emerging area of point-of-care ultrasound research. Identifying a skull fracture on ultrasound imaging in this age group requires knowledge of the appearance and location of sutures to distinguish them from fractures. There are currently no commercially available pediatric skull fracture models. We outline a novel approach to building a cost-effective, simple, high-fidelity pediatric skull fracture phantom to meet a unique training requirement.

Key Words—fracture; phantom; point-of-care ultrasound; skull; ultrasound

Developing accurate and inexpensive ultrasound simulation phantoms (simulated models for ultrasound training) is important for training in many ultrasound applications. Given the overuse of computed tomography in many pediatric conditions, the use of ultrasound in pediatric patients is of the highest priority. Head trauma is a leading cause of pediatric morbidity and mortality,[1,2] yet computed tomography is also overused in this condition, resulting in increased and unnecessary radiation exposure.[3] Therefore, ultrasound is increasingly being investigated for its accuracy in the detection of skull fractures in children. Several initial studies indicated sensitivities ranging from 82% to 100% and specificities ranging from 94% to 100% with pooled sensitivity of 94% and pooled specificity of 96% in the pediatric population.[4–7]

Learning to detect pediatric skull fractures with ultrasound, however, can be challenging given anatomic variations and the presence of cranial sutures. Having an accurate ultrasound phantom for training to detect pediatric skull fractures is therefore critical for training. In this article, we outline a novel approach to building a simple, inexpensive, high-fidelity pediatric skull fracture phantom to meet this unique training need.

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Background

Several commercial phantoms are available for training in point-of-care ultrasound. Currently, these products are expensive and have limited availability, and many have a limited lifespan. In addition, the production of commercially developed phantoms lags in comparison to the rapid evolution of point-of-care ultrasound practice. At this time, we are not aware of a commercially available skull fracture phantom. As a result, noncommercial phantoms are often created to fill a training need. Phantoms should ideally be inexpensive, easy to construct, realistic, durable, and reusable. We present a novel point-of-care ultrasound training phantom for identifying pediatric skull fractures and discuss its development and deployment.

Materials and Methods

When creating a high-fidelity static pediatric skull phantom, there are 2 elements to consider: (1) accurate representation of the younger-than-2-year-old pediatric skull; and (2) a sonographically accurate transmission medium. In choosing the required materials, we considered the size, accuracy of sound transmission, artifact generation, cost, and durability.

Our focus was to create a realistic phantom of a younger-than-2-year-old skull with and without fractures. In choosing a skull model, we determined that a rounded structure that would be a hard reflector, resist decomposition in liquid, and be easily cut was needed. We also considered the issues surrounding the developing pediatric skull. The average 1-year-old pediatric skull diameter is 45 cm, and the 2-year-old skull averages 47 cm.[8] A preformed structure that met these criteria would minimize the time and expense in creating this phantom.

Prefabricated plastic skulls as well as human specimens ranged in price from $100 to $450, and we regarded these as too costly. Many materials were tested; however, coconut cups serendipitously located at a local party supply shop yielded characteristics amenable for this application. The cups were echogenic, moderately easy to cut, inexpensive ($2.50 each), and approximated the size and shape of a 1- to 2-year-old skull. In addition, the cups were water resistant.

To best represent a pediatric skull, suture lines needed to be added to the phantom in anatomically correct locations and characteristics. This process was accomplished by using a black marker to draw on sutures and a fracture as a cutting guide. Cutting sutures into the skull was the only option considered to reproduce sutures and fractures with acceptable fidelity. However, the cutting of the coconut presented several challenges. The first and most surprising issue was the brittleness of the coconut. Several cutting tools were tested; however, a plug-in motorized hobby saw proved the safest and most efficient way to cut the coconut. A thin, reinforced ceramic disk blade provided the best lines. The cuts made by the motorized saw were somewhat linear, sharply defined, and approximated very well.

Suture lines in the pediatric skull, when visualized with point-of-care ultrasound imaging, are irregular and often approximate unevenly. In our experience, this factor is particularly true in children younger than 9 months. In contrast, ultrasound images of fractures appear linear and crisp, and often with overlap. Cuts made by the motorized saw showed the appearance of a fracture on ultrasound imaging.

To achieve realistic cranial sutures, a rounded grinding bit was applied to lightly grind irregularities into the cut edge that mimicked cranial sutures' irregular edges. Sandpaper was used to smooth and round areas that appeared sharp. We repeatedly reassessed how pieces approximated during this process. The sutures and fontanels were placed to approximate the anatomic structures of a human pediatric skull. Fractures were randomly placed. The resulting phantom consisted of several puzzle-like pieces (Figure 1). Tracing and cutting the sutures took approximately 30 minutes per coconut.

These pieces were reconstructed without overlap. We used several methods to maintain stability and proper orientation of the pieces while gluing the pieces together. After many failed attempts we found packing tape in combination with gum putty to work best. The packing tape was secured to the outer surface of the phantom as each piece was added until completely reconstructed. Gum putty

Figure 1. Coconut cut into puzzle-like pieces.

was then applied on the inner surface to maintain the separation between the pieces and reinforce the tape. Best results were achieved by placing the putty near the rim of the coconut where pieces were joined. We placed 3 or 4 small pieces of putty inside the phantom in areas that tended to overlap. Taping and puttying took approximately 15 minutes and was best done with an assistant.

When all pieces were cut, sanded, ground, and aligned, the coconut required permanent fixation. The fixation needed to meet the following several prerequisites: (1) it could not alter the echogenicity of the phantom; (2) a rapid drying time was desirable but not mandatory; (3) the adhesive needed to be durable and stable in a liquid environment; and (4) it had to be inexpensive. Several adhesive agents were tested. Five-minute epoxy gel proved to be the best agent, due to its quick drying time, high strength, adhesiveness to the coconut, ease of use, and viscous nature, which did not fill suture or fracture lines.

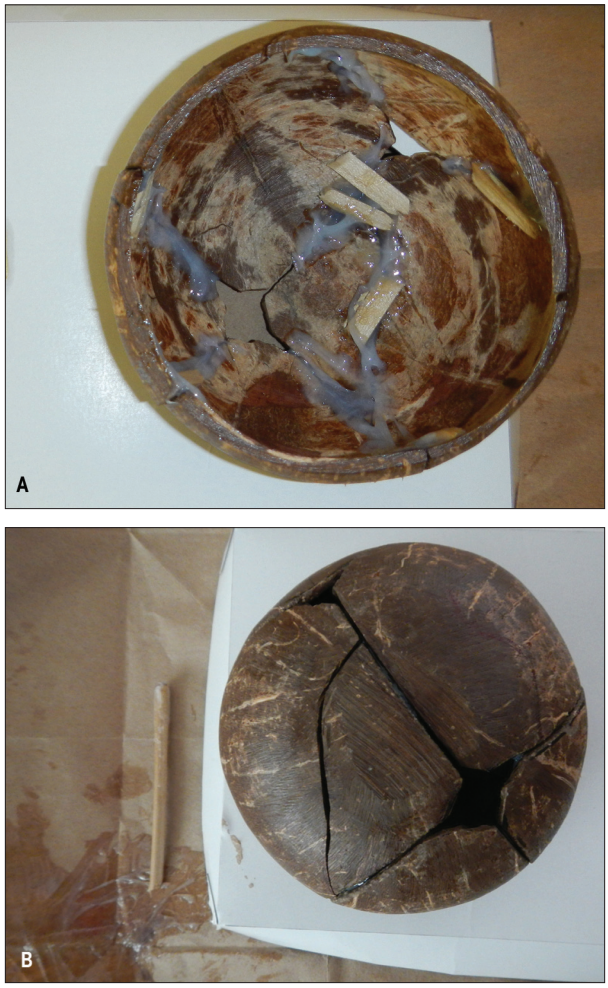
We applied the epoxy gel to the inner surface of the phantom to avoid altering the echogenic properties of the coconut and suture grooves. To allow more accuracy in its application, we mixed the epoxy gel for 2 minutes before applying, which increased its viscosity and decreased the drying time. This process aided in precise application of the epoxy and further resisted filling in the gaps of the sutures. Several 2-cm pieces of a ¼-inch wooden dowel were placed obliquely over the sutures on the inner table of the phantom within the gel epoxy while it dried to reinforce the structure. After the first application of epoxy was dry, the putty was removed. We then used a thin layer of epoxy gel to coat the suture areas not already glued on the inner table (Figure 2A reinforcing the inner table of the phantom skull; and Figure 2B, a completed phantom skull, viewed from the outside). This step took approximately 25 minutes.

Two additional steps proved to be necessary for both accuracy and durability of the phantom. Several prototype skulls proved that the phantom was not waterproof and difficult to submerge in the transmission medium. Waterproofness was necessary to reuse the phantom after taking it out of the gel transmission medium, which is discussed in the next section. To solve this problem, a waterproof shellac was applied in 2 thin coats 1 hour apart as a sealant. This application worked well and allowed multiple submersions in the water-based transmission medium without warping or cracking.

The final step in constructing the phantom helped improve the ease with which it was stabilized while submerged. The fabricated skull proved to be very buoyant with resulting instability in the transmission medium. To decrease movement, two 1.5-cm-long pieces of round wooden dowels were attached to the convexity of the skull phantom 1 cm from the midsagittal suture on each side (Figure 3). These were used to space the skull from the bottom of the container and add stability while the transmission medium solidified. We also affixed a large dowel to the middle of the inside of the phantom, protruding approximately 25 cm from its underside. This dowel was used as a stabilizing handle and gave the phantom the appearance of a lollipop (Figure 4). The coconut skull phantom was then allowed to dry overnight in ambient conditions. This step completed the construction of the "skull."

The next step was placing the skull into a sonographically accurate transmission medium. This step involved the selection of a transmission medium and the process of suspending this phantom in the medium. We used the

Figure 2. **A**, Reinforcement of the inner table. **B**, Appearance from the outside.



sugar-free gelatin and Metamucil (Procter & Gamble, Cincinnati, OH) solution described in a 1995 publication by Bude and Adler.[9] Approximately 750 mL was necessary per phantom. As had been described by Bude and Adler,[9] after approximately 3 weeks of refrigeration, the gelatin became dehydrated, moldy, and unusable. The shellacked skull portion of the phantom was extracted from the transmission medium and resubmerged multiple times with great durability.

The process of placing the coconut into the gelatin transmission medium required considerable attention. We selected a container based on its half-spherical shape, heat resistance, and approximate size in relation to the coconut. This container was waterproof and 15 cm in diameter × 7.5 cm deep. The prototype phantom was put in position, and the gel transmission medium was used to fill the container to within ½ inch from the top. We clamped or taped the dowel protruding from the underside to stabilize the skull in the desired position while the gelatin mixture solidified.

The stabilized phantom construct was cooled in a refrigerator for a minimum of 4 hours. Subsequently, it was easily remove from the mold. The protruding dowel was cut flush with the gelatin mixture, and the finished phantom was placed on its flat surface (Figure 5).

Results

A total of 3 pediatric skull phantoms were constructed. Through an extensive trial-and-error process, a high-fidelity pediatric skull fracture phantom was produced. The ultrasound images of the phantom were very similar to those seen during point-of-care ultrasound evaluations of true pediatric skull fractures (Figures 6–11). The final-product phantoms are realistic, durable, reusable, and inexpensive to make.

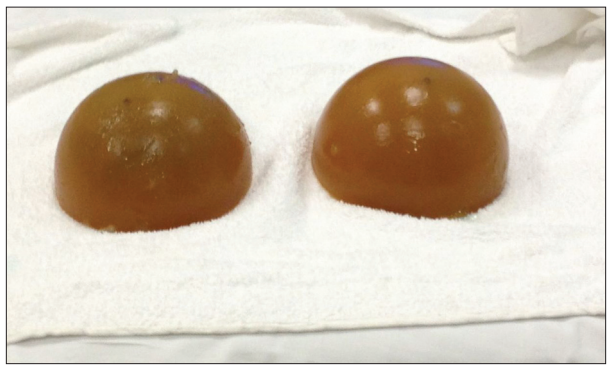
Figure 3. Dowel pieces attached to the phantom.

Discussion

Point-of-care ultrasound has increased the physician's bedside diagnostic capabilities. Innovation in this field has increased the breadth of applications, resulting in training needs. Many of these trainees are in medical schools and residencies, which have limited budgets and are unable to afford expensive commercial phantoms. Low-cost, reusable, realistic phantoms allow hands-on training for what would otherwise be taught with limited effectiveness through videos or images alone. This factor is especially true for low-frequency events, which trainees may see infrequently, resulting in insufficient training.

Figure 4. Lollipop appearance.

Figure 5. Two finished phantoms.



Hands-on workshops to detect skull fractures were held for both emergency medicine residents and attending physicians. Videos of true skull fractures, sutures, and fontanels were reviewed while scanning the phantoms. During the training, attending physicians and residents frequently commented on the similarity of the appearance of the true anatomy and skull phantom. In addition, performing point-of-care ultrasound evaluations of a rounded

Figure 6. Phantom suture line (arrow).

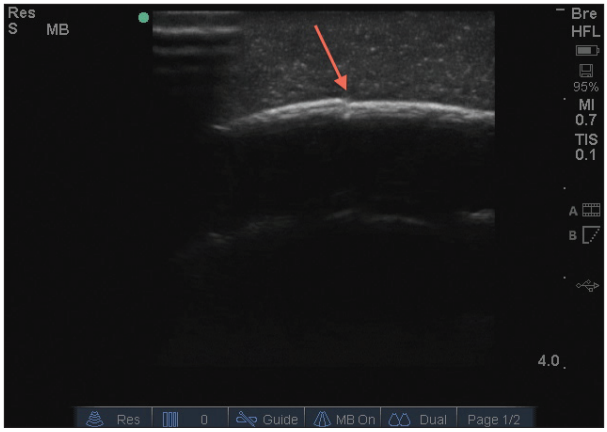


Figure 7. Phantom fracture (arrow).

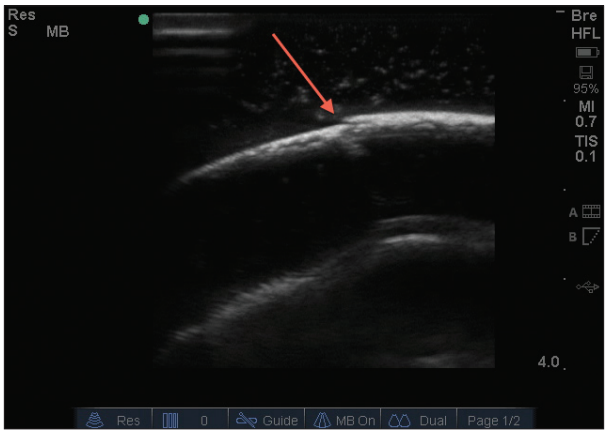


Figure 8. Phantom fontanel (arrow).

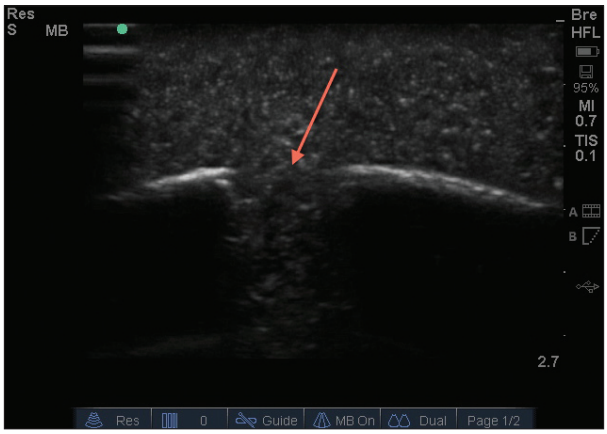


Figure 9. Human sutures (arrows).

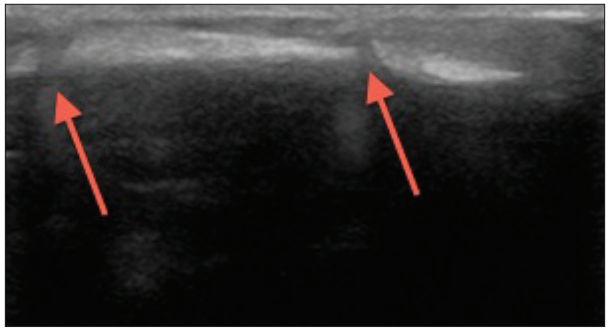


Figure 10. Human fracture (arrow).

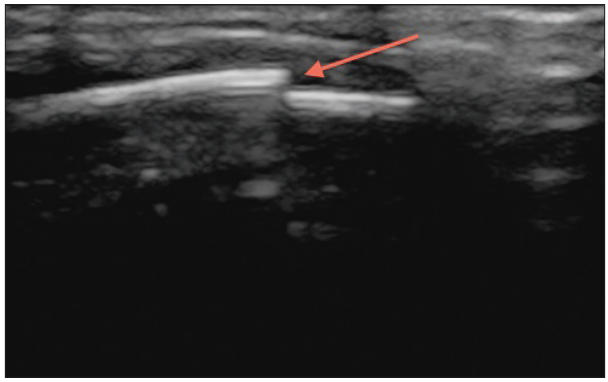
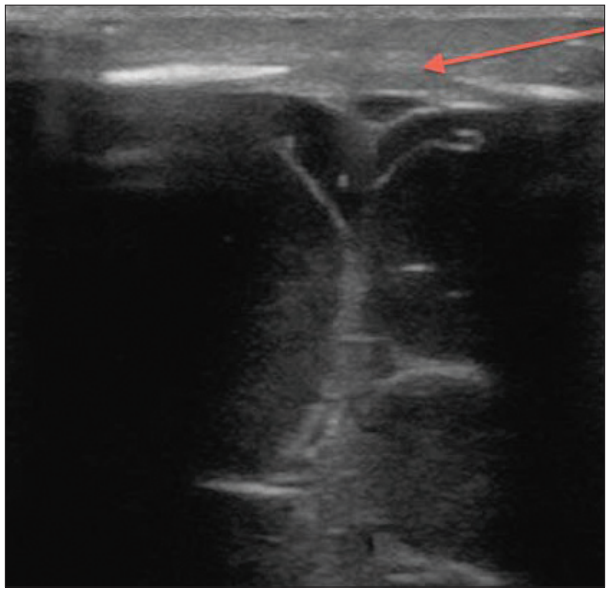


Figure 11. Human fontanel (arrow).



gel phantom proved to be technically challenging and required operators to use proper stabilization techniques to obtain consistent, high-quality images true to real-life scanning. Before these phantoms can be adopted as standard training tools, further study should look to validate whether trainees can identify fractures versus sutures with the same sensitivity and specificity cited in clinical practice literature.

This pediatric skull fracture phantom has several limitations. The materials used may not be available to each fabricator or may not exactly correlate with the materials purchased for these phantoms (Appendix). For each step, we entertained a long list of building materials and methods, which resulted in many failed prototypes. For brevity and focus, this article comments on our best process. Although we were not successful in applying many materials and methods, others may develop a process that yields a successful phantom. In addition, although we went to great lengths to accurately describe each major step, there were minor steps that may not have been described and will be up to the fabricator to intuit during the building process. Last, a moderate level of "handiness" with tools and construction processes is required to achieve the desired outcome. Without these skills the operator may sustain an injury, and the finished product may vary considerably.

In conclusion, this article provides a detailed description of a process used to create a high-fidelity pediatric skull fracture ultrasound phantom for point-of-care ultrasound training. We hope this detailed description and images assist those who choose to re-create this phantom and inspire others to create novel teaching phantoms for point-of-care ultrasound.

Appendix

Materials for Constructing a Skull Phantom
- 36–47-cm-diameter (15–19-inch) coconut cup
- ¼-inch-diameter round wooden dowel: 20 inches/skull (excess used for the suspension process)
- 5-min epoxy gel
- Waterproof shellac
- 5-inch packing tape
- Putty

Tools
- Leather gloves
- Safety goggles
- Plug-in mechanical hobby saw
- Cutting disk: as thin as feasible
- Grinding bit
- Cutting pliers (optional)
- 30–60-grit sandpaper
- Black permanent felt marker

Materials for Suspending the Phantom in the Transmission Medium
- 15-cm-diameter × 7.5-cm deep half-sphere–shaped container
- Sugar-free gelatin
- Sugar-free Metamucil
- ≈750 mL water
- 25-cm remaining dowel

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