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3D printed ultrasound phantoms for clinical training

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Abstract

Ultrasound is a ubiquitous, portable structural imaging technique which is used to provide visual feedback for a range of diagnostic and surgical techniques. Training for these techniques demands a range of teaching models tailored for each application. Existing anatomical models are often overly simple or prohibitively expensive, causing difficulties in obtaining patient or procedure specific models. In this study we present ultrasonic rib phantoms for clinical teaching and training purposes, fabricated by three-dimensional (3D) printing technologies. Models were produced using freely available software and data, and their effectiveness as teaching phantoms evaluated using clinical ultrasound scans of the phantoms.

Introduction

Clinical ultrasound (USS) is an imaging technique that takes advantage of the effective transmission of high-frequency acoustic waves through soft tissue. USS waves partially reflect off changes in tissue acoustic impedance, and the timings of the echoes are used to create a map of reflective interfaces as a function of depth. Most modern clinical systems make use of multi-element arrays that allow 2D structural *in-vivo* images to be obtained in real-time.[1] Although most widely used in imaging developing fetuses as part of normal pre-natal care it is a widely used diagnostic imaging modality and is also used at higher intensities to elicit therapeutic effects.[2] Furthermore, as a real time, handheld imaging system capable of discriminating between different soft tissue structures and solid surgical tools, it offers the potential for real-time monitoring of minimally invasive surgical interventions.[3], [4] However, for real time imaging of procedures in the torso, the presence of the ribs, which also represent a practical surgical consideration, is problematic. Due to the large difference in sound speed, density, and acoustic attenuation between bone and soft tissues, the presence of bone in the USS field can degrade imaging quality.[5] Images showing the impact of the ribs on USS, specifically reflections and shadowing, are shown in Figure 1.

As a result of these difficulties, clinical training for these interventions is improved by the use of anatomically and ultrasonically accurate teaching phantoms. However, commercially available phantoms can be prohibitively expensive.[4] Experimental studies examining imaging and therapy through the ribs and skull often use *ex-vivo* human or animal tissue. However numerous studies have also examined the potential of using 3D printing techniques to produce ultrasonic imaging phantoms of the head and other tissues.[4], [6] In addition, 3D printed thorax/rib phantoms for radiation dosimetry have previously been demonstrated.[7] 3D printing offers multiple advantages for phantom production, including the potential for printing and prototyping at relatively low cost. For complex anatomy and clinical cases patient specific models could be directly produced from medical image data for maximum effectiveness.[8] Open source models and the details of their production can be freely shared and edited, allowing tailoring of models to specific applications.

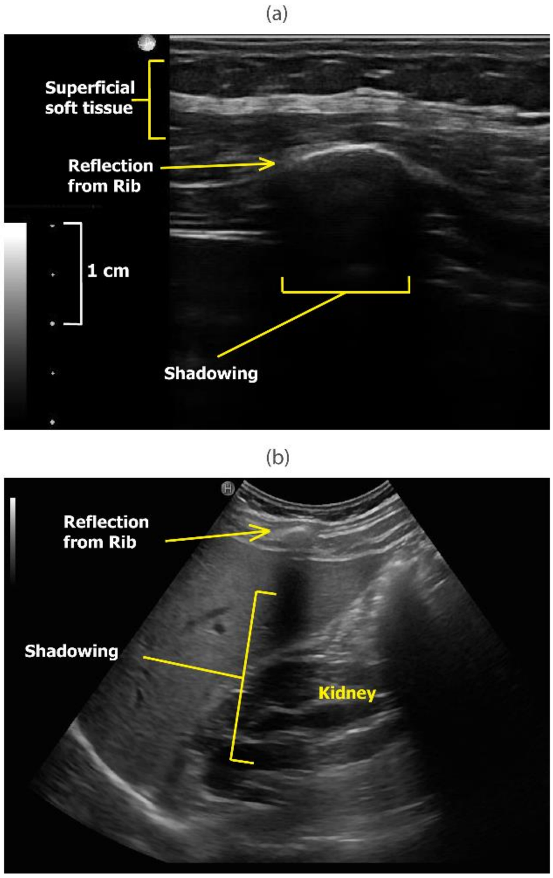

Figure 1. Anonymized ultrasound scans demonstrating the impact of ribs on ultrasound imaging. (a) An ultrasound image of a rib showing the clear reflection from the rib. (b) Ultrasound image of kidney showing the shadowing effect of a rib in the ultrasonic field.

For the present paper, clinical partners identified a requirement for practical rib and kidney phantoms for use in surgical teaching and planning of complex cases, specifically needle biopsy of the kidney, which lies at the back of the body, deep to the lower three ribs. To be useful as teaching aids, the models should provide a realistic imitation of real tissue and anatomy when imaged using clinical USS systems. They should also mimic the gross morphology and tactile response expected while performing a needle biopsy in order to prepare trainees for the unique difficulties posed. Freely available segmentation and mesh manipulation software was used to generate a rib model phantom from CT image data. This model was then incorporated into a mount system using computer aided design (CAD) techniques to allow use as a biopsy training phantom. We produced a series of high quality 3D printed functional models

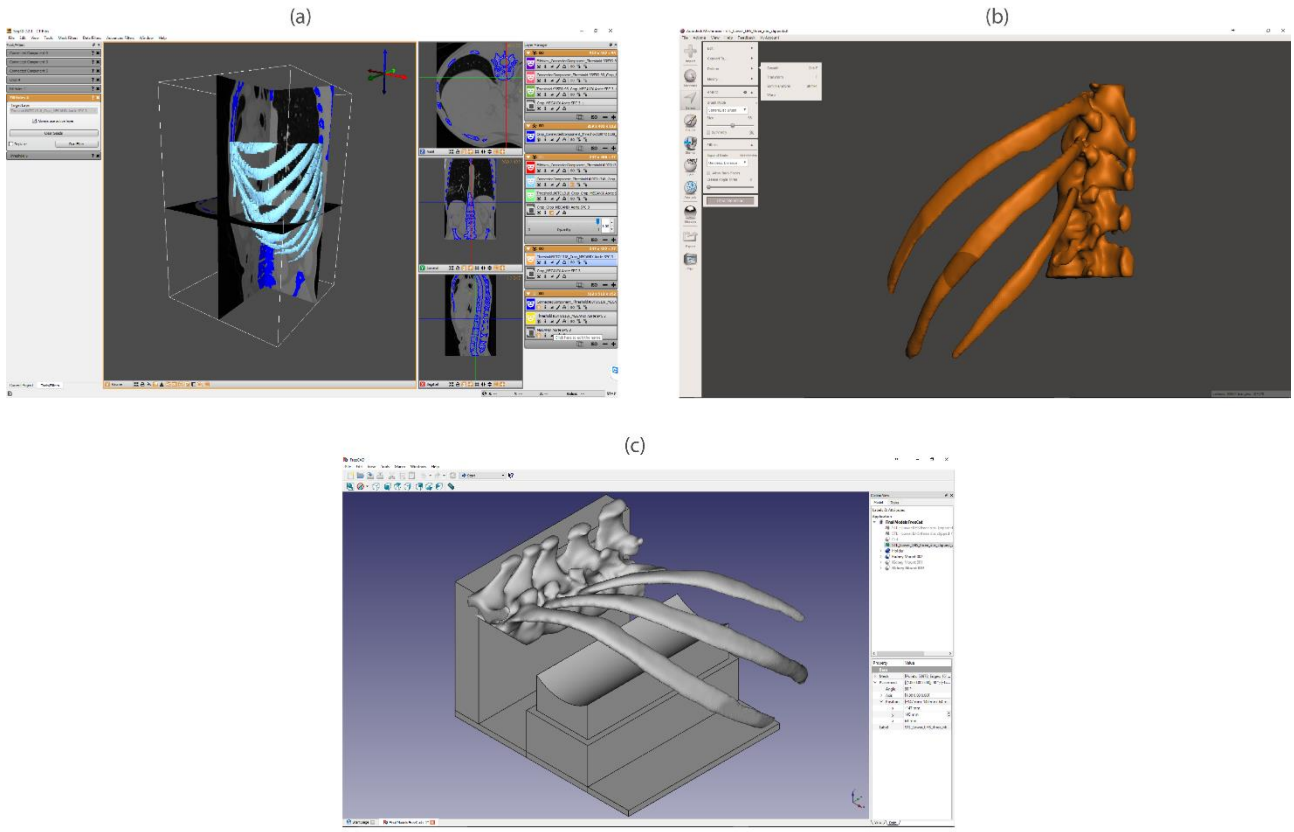

Figure 2. Examples of software used in rib model design. (a) Segmentation of CT dataset in Seg3D environment, showing raw segmentation and 3D model cropped to appropriate volume. (b) Refined model in MeshMixer™ environment following additional cropping and smoothing using MeshMixer utilities. (c) Design of mount for kidney phantom alongside finished rib model in FreeCAD software.

of selected sets of ribs for use in clinical training for USS guided therapy and diagnostics. Clinical partners advised on specific design considerations for these models. USS scans of the resulting ribs were used to confirm the ultrasonic profile of the phantoms, and mock biopsy carried out to evaluate their form, USS image profile and tactile feedback.

Image Segmentation and Cropping

To generate the rib model, freely available X-Ray Computed Tomography (CT) images were obtained from the OSIRIX website.[9] CT images were used due to their excellent bone tissue contrast. The MECANIX dataset, comprising a complete torso image was used. A range of freely available software was used to segment and refine the rib model, and to incorporate it into a holder that would allow its use as a training tool. The segmentation, refinement, and CAD processes are described below, in terms of the specific actions carried out in the primary software used.

Seg 3D

Segmentation and initial process of the MECANIX CT data was carried out using the open source Seg3D software (http://www.sci.utah.edu/cibc-software/seg3d.html).[10] This freely available software uses a layer based environment to allow the creation and manipulation of multiple segmentations in parallel. An example of the Seg3D user interface including the MECANIX torso CT dataset and rib segmentation is shown in Fig 2. (a).

Thresholding

The first stage of the segmentation was intensity based thresholding of the CT dataset in order to extract the bone tissue volume within the image. Thresholding was carried out using a Hounsefield Units (HU) band of 100-1318, which allowed effective selection of the bone tissue in the image. However some artefacts and erroneous volumes were also included in the segmentation.

Cropping

Based on the advice of clinical partners, the design of the phantom was to comprise the bottom three ribs (including two "floating" ribs) on the left hand side of the body, representing the most challenging clinical scenario. Spatial cropping tools were used to restrict the threshold segmentation to an appropriate cuboid volume of space. The cropped segmentation volume is visible in Fig 2. (a).

Connected Component

Once an appropriate rib volume had been derived from main image, the final step was the removal of remaining artefacts from the segmentation process. The Seg3D connected component algorithm allows isolation of a single contiguous volume based on seed markers placed on the segmented volume of interest. For this segmentation, five seed markers were placed on individual ribs, and the Seg3D connected component algorithm used to isolate the correct volume.

The completed segmentation was exported from Seg3D as a 3D stereolithography (STL) file for further processing.

MeshMixer™

Following the creation of an initial segmented model in the Seg 3D software, it was necessary to refine the model further. AutoDesk® MeshMixer™ (http://www.meshmixer.com/) is a freely available mesh manipulation software with many useful functionalities, which can directly load the STL output from Seg3D. The MeshMixer™ environment is shown in Fig 2. (b) demonstrating the completed rib model following refinement.

Cropping:

Although the model was previously cropped to a specific cuboidal volume of space in Seg3D, the gross morphology of the mesh model required additional cropping & cleaning before being useable. Plane cut and paintbrush tools were used to remove any remaining artefacts, and the extra ribs contained within the cuboid segmentation volume.

Smoothing

A consequence of the segmentation of a voxel based CT image is the inclusion of staircasing artefacts in the resulting 3D surface. The MeshMixer™ smoothing tool was used and applied to the entire segmentation to correct these CT artefacts and produce a smooth, anatomically realistic rib model. The MeshMixer™ smooth tool was employed using default settings, and the smoothed rib model is shown in Fig. 2. (b).

Once the model refinement was complete, the finished model was exported as an STL file.

FreeCAD

The rib model described above only forms part of a clinical training system that must also include a kidney phantom and mounting framework for holding them all in place. Therefore the next step was the incorporation of the anatomical structure into a mounting system. This system was designed using FreeCAD (http://www.freecadweb.org/), a freely available CAD software that can rapidly design objects based on simple 3D geometrical shapes. The FreeCAD environment is shown in Fig. 2. (c).

Mount Design

Initially, the mounting system was designed in FreeCAD from simple geometrical parts. The mounting system comprises a horizontal base and vertical backplate. The base was designed with a rack into which kidney stands of a variable height can be placed in order to position the kidney phantom in the desired position. The backplate was designed with a slot which would allow an appropriately modified rib model to be mounted. Three kidney stands of variable height were also designed

Model-Mount interface

Following the design of a rib and kidney phantom mount, it was necessary to append the previously constructed rib phantom with a mounting block that can be slotted into the backplate of the mount. The mounting block was designed and aligned with the rib model in FreeCAD, and then exported to the freely available Blender software (https://www.blender.org/). Although primarily an animation software, Blender has multiple useful mesh manipulation tools, and allows for operations on very large mesh models. Here it was used to connect the rib model to the mounting block.

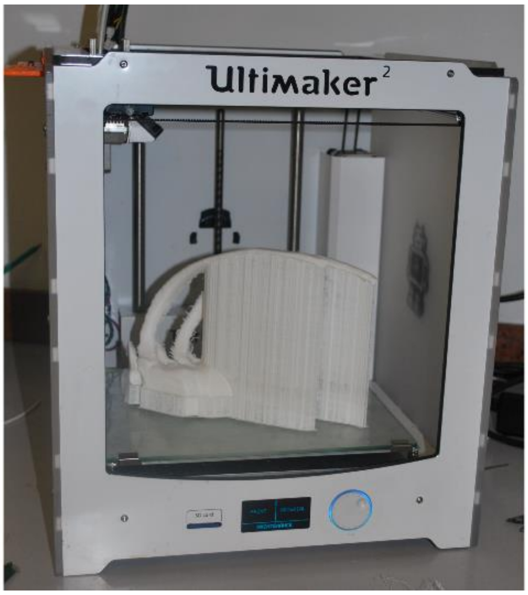

Figure 3. Completed 3D print of rib model, including mount and extensive support material required for rib overhang

The completed model, in combination with the rib phantom and with a kidney mounting block in place, is shown in Fig. 2. (c). Each model was exported individually as an STL file ready for printing.

Model Production

3D Printing

Rib models and mounts were 3D printed on an Ultimaker 2.0 printer in Polymaker, enhanced Polymax PolyLactic Acid (PLA). The Ultimaker printer is a fused deposition modeling (FDM) printer which works by depositing layers of print material from a nozzle, which moves in the horizontal plane, onto a print bed, which moves vertically. The Polymax material was chosen due to its relatively low cost, availability, and predicted ultrasonic reflectiveness. The enhanced PLA allows higher build quality and a reduced print failure rate.

The STL files for the rib model, mount and kidneys stands were separately loaded into the Ultimaker CURA 3D printing software. This software allows selection of print options, and generates the gcode files used by the Ultimaker printer. Two

Table 1: CURA Ultimaker 2.0 Print Settings

Model	Rib	Mount
Layer Height	0.1 mm	0.1 mm
Shell Thickness	0.8 mm	0.8 mm
Infill	100%	20%
Travel Speed	100 mms^{-1}	100 mms^{-1}
Nozzle Size	0.4 mm	0.4 mm
Material	41.28 m	32.12 m
Print time	62:31 hrs:mins	24:58 hrs:mins

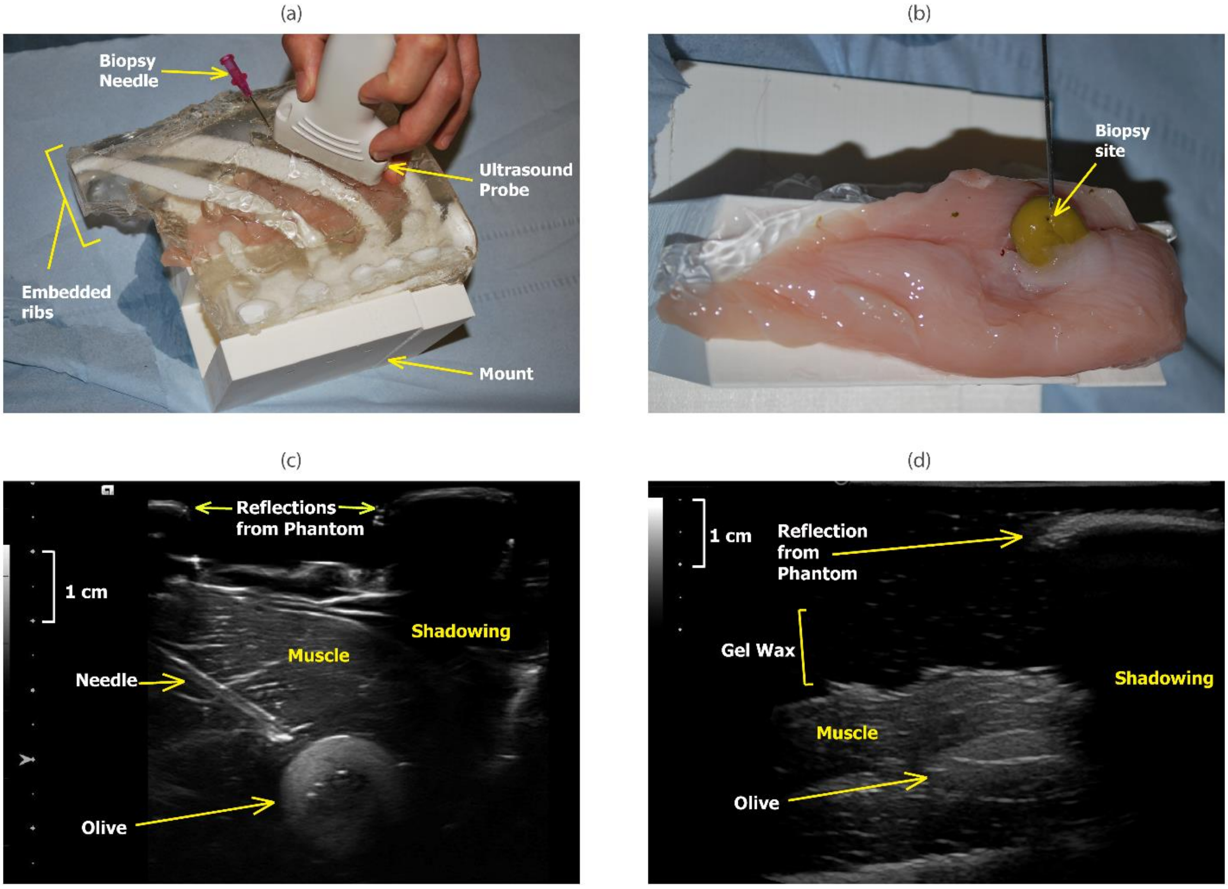

Figure 4. Ultrasound scans of the rib and kidney phantom setup. (a) Ultrasound scan setup for embedded model, showing mounting system and biopsy needle. (b) Chicken kidney phantom following biopsy, showing needle mark. (c) Ultrasound image of the non-embedded rib and kidney phantoms suspended in a water bath, showing reflection and shadowing from the rib, and a needle targeted at the olive target. (d) Ultrasound imaged of the rib phantom embedded in Gel Wax and kidney phantom, demonstrating reflection and shadowing from the phantom, as well as the ultrasonic profile of Gel Wax material.

copies of the final rib model were printed. Due to the constraints of the ultimaker printer, the models were both printed at 90% size compared to the original CT image. At this scaling, the model is still anatomically relevant for adults, and corresponds approximately to the expected difference between male and female anatomy. The print settings used for both the rib models and mount system are shown in Table 1, alongside the print time and length of material used. The mount model comprised the mount base and a single mounting block. Based on these values, the approximate costs of rib and mount models are £14/$21 and £11/$16.5 respectively. It should be noted that these values include support material. The completed rib print is shown inside the Ultimaker printer in Fig. 3. Following printing, support material was removed with pliers, and the inferior surface of the prints smoothed with sandpaper.

Gel Wax Embedding

In order to provide tactile feedback during needle biopsy training, the possibility of embedding the rib model in an oil based, ultrasonically transparent, castable gel wax was examined. The gel wax acts as a soft-tissue mimic, in terms of both the ultrasonic image profile and tactile response. One of the two printed rib models was arranged inside a plastic box mold such that the posterior portion of the ribs would be well embedded within the gel following casting. The gel was heated until melted before being degassed in a vacuum chamber to remove any air bubbles. Due to the relatively low melting point of PLA (~150 °C), and the potential for heat deformation, it was necessary to wait for it to cool to near solid (~ 75 °C) before casting. The cooled gel wax was poured into the mold where it covered the ribs, and was left to set. Following cooling the embedded ribs were removed from the mold, and excess gel cut away, including a space to accommodate a kidney phantom. The embedded ribs are shown in Fig. 4. (a). The gel wax used cost ~£5/$7.5, and can be reused and recast multiple times.

Ultrasound Scans of Final Models

In order to evaluate the usefulness of the rib models as USS training phantoms, both were imaged using clinical USS systems, and trialed by performing mock needle biopsies. In place of a specially developed kidney model, an *ad hoc* model was created out of chicken breast and an olive, representing kindey soft-tissue and a heterogeneity (such as a kidney stone or tumour), respectively. This kidney phantom is shown in Fig. 4. (b). It was imaged through both embedded and non-embedded rib models, and a mock biopsy carried out to evaluate the models' effectiveness as teaching phantoms.

The non-embedded rib model and kidney phantom were placed within a deionized water bath and imaged using a Siemens Acuson S1000 clinical USS system with a high resolution USS probe (16 MHz) and a mechanical index (MI) of 0.5. The embedded model was imaged using a Hitachi Hivision Ascendus clinical USS system, also with a high resolution (16 MHz) probe, with a MI of 1. The embedded model was not placed in a water bath, although a thin layer of ultrasonic coupling gel was required to couple the kidney phantom to the gel of the phantom. The imaging setup is shown in Fig. 4. (a), including a USS probe and needle used to perform the biopsy.

The resulting USS scans for non-embedded and embedded USS scans are shown in Fig. 4. (c) & (d) respectively. Both clearly demonstrate reflection and shadowing from the rib phantom affecting the viewing of the kidney phantom. The biopsy needle and olive-heterogeneity can also clearly be seen in Fig. 4. (c). The embedding of the ribs in gel allows the kidney phantom to be positioned at a more appropriate distance from the rib model, and allows the kidney to be discriminated from a separate soft tissue surrogate. The mock biopsy was performed successfully in each case, with both embedded and non-embedded phantoms providing a good imitation of the impact of the ribs on imaging and needle insertion. However, the gel wax used to embed one of the model gave more realistic tactile feedback while performing the biopsy, resembling the response of soft tissue to a biopsy needle.

Discussion & Future Work

The final rib model and mounting system designed and produced above represents a functional system for clinical training of interventional USS imaging for minimally invasive kidney surgery. The total cost of a single embedded phantom and mounting block was approximately £30/$45, which represents a significant saving relative to commercially available phantoms. It is possible that these costs could be reduced further while maintaining build quality and ultrasonic profile by reducing the infill density of the rib model, and designing custom support structures. It is also possible that a smaller, and therefore cheaper, model comprising the posterior portion of the three ribs of interest, would suffice for some training procedure. A key advantage of 3D printing and CAD techniques is that the phantom design could easily be altered to accommodate this. In addition to the specific rib models produced, the design process outlined above can be used to reproduce the rib model, and the general pipeline can be applied to alternate medical image data to produce similar 3D printable models of ribs and other bone structures. This pipeline, along with a range of associated information on 3D printing techniques have been collected, and are available to view at http://www.3d-med.co.uk/.

Some limitations in the completed models are apparent, which should be addressed as the model is developed further. Although the PLA material is very effective at reflecting USS, resulting in shadowing and reflection in the USS image, it does not resemble the behavior of bone perfectly. PLA ribs are excessively reflective, with limited transmission of ultrasound relative to real ribs. This is likely due to air trapped within the PLA during the FDM process, which would prevent USS transmission and cause total reflection of incident USS. For the purposes of clinical training this is not a problem, as the most important attributes of ribs in this context are their reflection and shadowing, but it is possible that an alternative 3D printing technique and/or material would provide a more realistic USS image. Similarly, the embedding gel material, although it provides excellent tactile feedback for the biopsy process, is more ultrasonically transparent than normal soft tissues such as muscle and renal cortex. This can be seen in the comparison of the USS images in Figs. 1 & 4. Practical production of the embedded ribs is contingent on access to a castable soft tissue phantom, and the process of heating and casting could be streamlined further, perhaps with the addition of a 3D printed casting mold. Recasting of the gel between usages would also address the problem of needle track lines, which remain in the gel following mock biopsy and are visible on ultrasound images.

With these limitations in mind, the rib phantom, and associated production pipeline will continue to be developed to form part of a complete clinical training phantom for interventional USS procedures. Alternate rib model geometries and 3D printing techniques will be used to produce additional rib models, which will be compared with the present model. Adulterants could be added to the gel wax to make it resemble soft-tissue more accurately in ultrasound images. In addition a reproducible method for fast casting of gel wax and effective embedding of rib model, should be created to allow rapid and standardized production of embedded rib models. The ultimate goal is the incorporation of the developed models and production techniques into a set of phantoms for clinical training, including kidney and liver phantoms.

Conclusions

A 3-D printed, PLA based rib phantom and mounting system was produced from medical imaging data, and its usefulness as a clinical training phantom evaluated using USS scans and performing a mock kidney biopsy. Test ultrasound images of the combined rib and kidney phantoms demonstrated a good imitation of the characteristic reflection and shadowing resulting from ribs. Mock biopsies confirmed the utility of the system as a clinical training phantom, and demonstrated the advantage of embedding the ribs in a gel wax soft tissue mimic.

The rib model, mounting system, and production pipeline will continue to be developed and streamlined in order to reduce costs, improve performance as a training phantom, and to allow the system to be easily reproduced. As 3D printing becomes more widely available, the developed clinical training system and its production pipeline will help facilitate widespread access to anatomically accurate, patient specific models, tailored for the training of complex interventional USS procedures.

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