Evaluation of the Accuracy of 3-Dimensional Ultrasonography of the Kidney Using an In Vitro Renal Model

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Objective. Three-dimensional ultrasonography (3DUS) has recently become a reality because of advances in ultrasound probes and machine processing ability. We have developed an anthropomorphic phantom of the human loin to assess both the accuracy of 3DUS of the kidney and its potential usefulness for training in ultrasonographically guided percutaneous renal intervention.

Methods. The model was built with easily available and inexpensive materials such as agar and latex with known ultrasonographic properties. The accuracy of 2-dimensional ultrasonography (2DUS) and 3DUS was assessed by measuring the dimensions of the pelvicalyceal system (PCS) ultrasonographically (pelvis width and calyx diameters) and then comparing these with measurements obtained at the time of construction. Radiology interventional trainees then punctured the PCS with 2DUS and 4-dimensional ultrasonographic (real-time/time-resolved 3DUS) guidance and reported the phantom’s performance.

Results. The 3-dimensional nature of the model’s PCS could be clearly visualized on 2DUS and 3DUS, and the scan characteristics were very similar to those in real life. Measurements using 3DUS proved to be closer to the true dimensions of the model’s PCS than those using 2DUS. The mean error percentage for 2DUS measurements was −10.2%, and that for 3DUS was −2.2% (P < 0.0001). Interventionsal trainees were satisfied with the “tissue feel” and level of difficulty posed on puncturing the phantom.

Conclusions. Three-dimensional ultrasonography proved to be more accurate than 2DUS for intrarenal measurements using this in vitro renal model. Three-dimensional ultrasonography has the potential to ease diagnostic renal scanning with the ability to further scrutinize and postprocess the scanned volumes. The model was realistic in its anthropomorphic properties and simulated human tissue during puncture.

Key words: imaging phantoms; interventional ultrasonography; kidney calices; kidney pelvis; measurement; 3-dimensional imaging; ultrasonography.
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2-dimensional ultrasonography (2DUS) in the highly complex anatomy of the renal pelvicalyceal system (PCS). An accepted method for assessing ultrasonographic accuracy is by distance and volume measurements, initially on phantoms and then at the bedside. Such comparisons can, however, present difficulties. For example, variations in measurements of renal structures can occur because of the kidney’s anatomic position in the human body, and multiple ultrasonographic views are needed to be accurate. Three-dimensional ultrasonography is also prone to the same artifacts and errors as 2DUS.

Anthropomorphic ultrasonographic phantoms are a challenge to manufacture because of the need to accurately recreate the anatomic appearance and ultrasonographic characteristics of human organs. To date, several substances have been identified as adipose and nonadipose tissue-equivalent (TE) material such as animal hide gelatin, graphite powder, and agar. Models should also recreate the anatomic limitations encountered in real life, such as the intervening ribs and bowel shadows.

We set out to develop an abdominal anthropomorphic phantom to evaluate the accuracy of 3DUS compared with conventional 2DUS, using measurements of the renal PCS as the reference standard (pelvis width and calyx diameters). We chose measurements of the PCS rather than a simple visual grading of the distension of the renal pelvis and calices to ensure accuracy and reproducibility of the study. It would also enable detailed statistical analysis and objective comparison between 3DUS and 2DUS. A preliminary assessment was also made of its usefulness for training in renal ultrasonography and percutaneous interventional procedures by puncturing it with both 2DUS and 4DUS guidance.

Materials and Methods

Manufacture of an Anthropomorphic Renal Phantom

The TE material used was agar based and manufactured by the hospital’s clinical physics department. The mixture contained benzyl chloride to prevent bacterial colonization and was degassed in a vacuum chamber. The speed of sound in this mixture was 1540 ± 3 m/s (as determined by time-of-flight measurements on samples of the TE material, with backscatter, attenuation, and their frequency dependence similar to that of average tissue). Its attenuation coefficient was 0.5 dB/cm/MHz. The speed of sound in latex is 1550 ± 10 m/s, and with a hyperechoic interface on ultrasonography, it was ideally suited for making the PCS as well as simulating renal sinus fat and fascial layers. The ability of thick latex to retain its shape also renders it impervious to leaks from punctures.

The phantom was designed to simulate a median plane cut section of the right half of the abdomen with the midaxillary line in the uppermost position (Figure 1). The initial part of the study involved manufacture of the kidney. The PCS was first modeled out of clay (Air-harden modeling clay; Calder Colours [Ashby] Ltd, Ashby-de-la-Zouch, England), and latex (latex emulsion; Specialist Crafts, Leicester, England) was then coated over. Previously created casts of a pig kidney PCS and pictures of casts of human kidneys were used as references to model the clay. There were 7 calices and infundibula in total. The shape of the tips of the calices was roughly circular. The clay model was dipped in the latex for 10 minutes (as recommended by the manufacturer) to reduce air bubble formation. This formed a uniform coat of latex, which was air dried. The clay was then smashed and washed out. The finished PCS is shown in Figure 2.

The fascial covering of the kidney was designed next. A clay model of the renal outline was made on a stand, allowing it to rest on the bench while being painted with latex emulsion. The latex was then removed by peeling it off the mold. This left...
2 openings in the shell, 1 at the ureteric extension and the other where the stand had been, which corresponded to the upper pole of the kidney phantom. The latex PCS was inserted through this upper pole opening into the kidney shell and secured with latex to the ureteric opening. To maintain uniform drying and a tight seal, a cylindrical wooden strut was inserted into the ureteric opening (Figure 3). Finally, TE material was poured into the kidney to form the parenchyma. The latex PCS was sufficiently sturdy enough to not lose its shape during the pouring of the TE material. A thin polyvinyl chloride pipe was attached to the ureteric stump with latex (Figure 4). This allowed the PCS to be filled with a radiopaque contrast agent after the model had been finished to facilitate interventional studies and fluoroscopic imaging.

An acrylic container with matching lid was built for the phantom. The vertebrae were first modeled with clay and then coated with plaster of paris, which contains air, giving it higher acoustic attenuation and making it a good bone mimic. Paravertebral muscles were simulated by placing layers of paper towel soaked in the TE material, as can be seen in Figure 4. The intestines were created by loading mashed TE material into condoms (in the case of the small bowel) and an ultrasound transducer cover (for the ascending colon). The space left after the kidney and intestines was made roughly liver shaped, and TE material was poured in to simulate the liver. Finally, TE material was poured in layers to simulate subcutaneous tissue and muscle. Two ribs (11th and 12th) were made by coating plaster of paris over rib-shaped clay. They were placed at a less than 1-cm depth to the surface to simulate their natural position over the upper pole of the right kidney. A layer of commercial ultrasound gel was added to maintain hydration of the TE material and to enhance the scan quality. The skin was created by painting layers of latex onto a glass surface and glued to the outer parts of the phantom. Figure 5 shows the finished phantom. The cost of making the phantom is difficult to estimate because a lot of the materials were “off the shelf” or taken from

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**Figure 2.** Latex PCS. The double-headed arrow indicates how the pelvis was measured (from the base of the fourth infundibulum to the line drawn across the pelvis).

**Figure 3.** Latex PCS. The view is through the “upper pole” of the kidney shell (Gerota’s fascia) looking at the PCS within (arrow).

**Figure 4.** Contents being added into the acrylic container.

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bulk quantities already present in the medical physics laboratory. However, the major cost factor here would be the human hours rather than materials, and we estimate the total cost of constructing the model to be approximately £200 (~$297).

The phantom was scanned using an iU22 ultrasound machine (Philips Medical Systems, Bothell, WA). Both 2DUS and 3DUS scans were performed with a 3D6-2 curvilinear array (Philips Medical Systems; Figures 6–8). To obtain 3DUS images, the transducer was initially positioned with the use of 2DUS where image parameters could be adjusted. The 3DUS software was then activated to perform a single sweep of the area based on a prespecified angle of acquisition (75°). The multiplanar reformatted (MPR) display shows the structure in 3 orthogonal planes as well as a volume-rendered image (Figure 8). Every image had a “crosshair,” which was the point of intersection of the 3 orthogonal planes. The crosshair on any one of the views could be selected and moved to another part of the image with the mouse on the machine's keyboard. This would result in all of the other views moving to the corresponding intersection of the 3 orthogonal planes. Selecting a view itself allowed scrolling through the acquired image. Thus, the calyx or area of interest could be focused on with ease in all 3 planes by this method. Stored 3DUS volumes could thus be manipulated with the software on the machine’s workstation.

**Figure 5.** Phantom. The view is looking directly at the top of the phantom, which corresponds to the anatomic right midaxillary line. The arrow points to the cranial end.

**Figure 6.** Longitudinal 2-dimensional scan of the phantom. 1, Liver; 2, PCS.

**Ultrasonographic Measurements**

For this, 2DUS and 3DUS scans were performed by 2 consultant radiologists (U.P. and J.P.). Three hours was allotted for each scanning modality, and there were fewer 3DUS scans because of the longer acquisition time. In the 2DUS mode, longitudinal and transverse sweeps of the kidney were made and stored in the cine mode. This was done to enable the best view of a calyx in a particular scan to be used for measurements. Three-dimensional scans were taken from both longitudinal and transverse reference views and stored as MPR images. Any of the views within an MPR image could be scrolled to get the best view of the calyx being measured. Calyx diameters and the pelvis width of the latex PCS measured at the time of construction were taken as reference standards. (Figure 2 shows how the pelvis was measured.) A set of measurements of calyx diameters and the pelvis width was obtained from each of the 2DUS images and 3DUS MPR images with the machine software's digital calipers and compared with the actual dimensions. All distance measurements were performed by the same investigator (B.S.J.), who was blinded to the actual dimensions of the PCS. A single investigator taking the ultrasonographic calyx diameter and pelvis width measurements in the model's complex renal PCS ensured uniformity of the method (such as optimum display of the structure being measured and consistent placement of the digital calipers). Where possible, measurements of calyx diameters were taken from longitudinal, transverse, and coronal views of a 3DUS MPR image, and the average value was taken.
Understandably, pelvis width measurements were possible on longitudinal and transverse views only. Longitudinal and transverse image results were not analyzed separately because of the roughly circular outer border of the calices. A graphic plot was constructed of differences of measurements (by each method) from the actual dimensions of the calices for analyses of the data spread as well as direct comparison of the two modalities. All statistical and graphic analyses were performed with Instat (GraphPad Software, Inc, San Diego, CA) and MedCalc (MedCalc Software, Mariakerke, Belgium).

Ultrasoundographically Guided Puncture
Interventional trainees with at least 3 years of experience in ultrasonographically guided intervention were asked to puncture the model with 2DUS and 4DUS guidance as a preliminary assessment of the model for renal intervention. Fifteen practice punctures (8 with 2DUS and 7 with 3DUS) were performed with a 21-gauge bore, 20-cm-long Chiba needle.

Results
The 3DUS volume acquisition was quick and did not take more than 3 seconds. The kidney and upper pole, lower pole, and interpolar anterior and posterior facing calices were seen well within the image. The anterior facing calices could be readily distinguished from the posterior calices. When scanning the upper pole of the kidney, there was image degradation because of ribs and enhancement over the liver lower down, similar to real life. The shape of the phantom provided adequate access for renal scanning. The simulated PCS was larger than normal, and the calices were more discrete to facilitate percutaneous access and measurements. The intrarenal calyceal and pelvic anatomy were clearly depicted, as shown in Figures 6 and 7, which are longitudinal and transverse 2DUS renal scans, respectively, of the phantom. Figure 8 shows corresponding 3DUS scan images with multiplanar reformatting as well as volume rendering.

Two scans in 2DUS and 1 in 3DUS could not be used for any measurements because of rib shadowing. There were a total of 11 2DUS and 9 3DUS scans, resulting in 72 and 110 measurements of calyx diameters and pelvis width, respectively. (There were many more measurements from 3DUS scans because it was possible to take measurements of the same calyx diameter or pelvis width from the 3 planes of an MPR image.) To reiterate, an MPR image offered up to 3 measurements (1 per orthogonal plane) of the same calyx. In such cases, the average value was taken for analysis for each set of measurements of a calyx; this approach has been described before.5,15 However, the clarity of 3DUS MPR images varied, and distance measurements from all 3 planes of an image were possible only in 34 of 64 sets of measurements (calyx diameter and pelvis width combined, 57.8%). Table 1 gives the actual calyx dimensions measured at the time of construction. Figure 9 is a graphic representation of the results. The plot values were obtained by subtracting true values of calyx diameters and the pelvis width from ultrasonographically obtained distance measurements and show that, on average, distance measurements from 3DUS scans were closer to the actual calyx and pelvis measurements than those from 2DUS scans. The lines

![Figure 7. Transverse 2-dimensional scan of the phantom. 1, Muscles; 2, ascending colon; 3, calyx.](image1)

![Figure 8. Three-dimensional scan of the phantom. 1–3, Multiplanar reformatting; 4, volume rendering.](image2)
show means ± 2 SDs. The results are summarized in Table 2 along with mean error percentages of 2DUS and 3DUS distance measurements.

The thin latex surface with ultrasound gel provided a realistic texture for scanning and lasted 3 months without breaking down. The model proved to be sufficiently realistic on puncturing, and the interventional trainees were satisfied with the "tissue-feel" and level of difficulty posed by it. During puncturing with 4DUS guidance, the needle could be seen mainly on the longitudinal and transverse views. This was best seen dynamically, videos of which we could not capture because of the limitations of the software available to us. The interventional trainees performed 15 punctures, after which they encountered problems with introduction of air and needle tracks that limited further puncturing. This was a design flaw and a limitation for further use of the model as an interventional trainer.

### Table 1. Measured Dimensions of the Latex Pelvicalyceal System

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Measurement, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calyx 1 diameter</td>
<td>0.89</td>
</tr>
<tr>
<td>Calyx 2 diameter</td>
<td>0.81</td>
</tr>
<tr>
<td>Calyx 3 diameter</td>
<td>0.83</td>
</tr>
<tr>
<td>Calyx 4 diameter</td>
<td>0.79</td>
</tr>
<tr>
<td>Calyx 5 diameter</td>
<td>0.98</td>
</tr>
<tr>
<td>Calyx 6 diameter</td>
<td>0.93</td>
</tr>
<tr>
<td>Calyx 7 diameter</td>
<td>0.89</td>
</tr>
<tr>
<td>Pelvis width</td>
<td>1</td>
</tr>
</tbody>
</table>

### Discussion

Our data have shown a significant difference between distance measurements taken with 3DUS MPR images compared with 2DUS, with 3DUS measurements being more accurate. Ninety-five percent of the 2DUS distance measurements were within 2 mm of the actual dimensions versus 1.8 mm for 3DUS, showing nearly equal variability between the distance measurements of the two scan modes. The mean error percentages of –10.2% for 2DUS and –2.2% for 3DUS (and their respective ranges) were larger than quoted in the literature, more so for 2DUS. This could have been for a few reasons. First, the borders of the latex calices were sometimes not seen clearly (which could have been attributed to the similar acoustic impedance of latex and agar, leading to an indistinct acoustic interface). Second, the tops of the calices were not perfectly flat but ellipsoid. Third, the calices were themselves angulated in the x, y, and z planes. The width of the pelvis measured as shown in Figure 3 was difficult to pinpoint accurately because the latex (like sinus fat) obscured the pelvis. All of these factors contributed to measurement errors but also added to the realistic nature of the model (in vivo renal calices are usually clearly defined only in grade 3 and 4 hydronephrosis). The appearance of the model’s calices is more akin to grade 2 hydronephrosis. There is a purported loss of resolution in 3DUS MPR images of views orthogonal to the reference plane. This explains why multiple image distance measurements could be taken in only 57.8% of sets of

### Table 2. Analysis of Distance Measurements (Calyceal Diameter and Pelvis Width) Taken From 2DUS and 3DUS Scans of the Phantom

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2DUS</th>
<th>3DUS</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values for analysis, n</td>
<td>72</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Mean of differences, cm</td>
<td>0.07</td>
<td>0.014</td>
<td>.002b</td>
</tr>
<tr>
<td>SD of above groups, cm</td>
<td>0.1</td>
<td>0.09</td>
<td>.013c</td>
</tr>
<tr>
<td>Mean error ± SD, %</td>
<td>–10.2 ± 8.6</td>
<td>–2.2 ± 8.3</td>
<td>&lt;.0001b</td>
</tr>
<tr>
<td>Range, %</td>
<td>–28.3 to 10.1</td>
<td>–16.3 to 22.8</td>
<td></td>
</tr>
</tbody>
</table>

CI indicates confidence interval.

*From actual calyceal dimensions.

*Unpaired t test.

*F test.
3DUS calyx and pelvis measurements. This availability of multiple views of the same calyx or renal pelvis (in 3DUS MPR images) also gave an average value for calyx diameters and the pelvis width and helped push the mean of 3DUS measurement differences closer to 0 (Figure 9).

We attempted as far as possible to use materials that minimized errors due to variations in the speed of sound. At a speed of sound considerably less than that in the liver (1447 m/s), the errors in distance measurements can be up to 3.3 mm (at a depth of 10 cm and separation of 6 cm) for convex transducers. Although the 2DUS errors in this study were quite large, the 3DUS mean error percentage was closer to what is acceptable in the literature (2%), suggesting that the fault was unlikely to be the materials used. Thus, large deviations from the actual values could be attributed to the ultrasonographic appearance of the targets in this model.

The model’s realistic nature on 3DUS has particular promise with the prospect of pure 4DUS-guided renal intervention and navigation. The ability to choose the optimum calyx for surgical purposes becomes readily apparent. Technical issues, such as ensuring secure wire placement for dilation, can be easily addressed (Figure 10). Compared with turkey breast and ex vivo biological renal interventional models, there is a clear advantage in using a more realistic phantom. While trying to puncture targets, the trainee faces the difficulties presented by overlying bone and tissue and gets a feel for multidirectional facing renal calices. The problem of air introduction and track formation in the agar during puncturing can be easily overcome by building a flat model with oil or water on top acting as a coupling agent, as described by Patel et al. The features of the phantom and image artifacts, similar to those of the human body, as well as the resistance of the layers of the phantom, offer additional challenges to the novice interventionist. Our interventional trainees were made only too aware of problems such as bending needles, accidental infundibular punctures, and adjusting for intervening ribs while puncturing the model.

Figure 9. Two- and 3-dimensional calyx diameter and pelvis width measurements: difference from the phantom’s measured dimensions.

Figure 10. Phantom being punctured with 4DUS guidance. The arrow points to the needle in the longitudinal section. Evidence of previous puncture attempts can be seen in panel 1 because of trapped air within needle tracts.
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Several other surrogate models have been constructed, such as porcine kidney models with ureters in foam, silicone, and whole chickens. They provide familiarity with calyceal anatomy and practice with instruments, tract placement, and dilation. At a time when several new stone treatments such as shock wave lithotripsy were coming into vogue, a canine model was also conceived for placing stones and assessing the effects of stone treatment in vivo. Krombach et al performed experiments on in vivo ultrasonographically guided nephrostomy placement with magnetic field navigation in pigs. They all have their own advantages, although there are some drawbacks, such as biodegradation, ethical considerations, and the lack of simulation of the abdomen in ex vivo models.

In conclusion, we have created a realistic anthropomorphic renal ultrasonographic model and have further shown that in vitro 3DUS renal pelvicalyceal distance measurements can be more accurate than 2DUS measurements. Three- and 4-dimensional ultrasonography have made huge strides in recent years in both diagnostic and interventional studies. With improving technology such as phased array systems, the problems with resolution can be eliminated, and 3DUS and 4DUS could in some cases replace computed tomography and magnetic resonance imaging as first-line diagnostic tools.

References