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Design of a kidney phantom for ultrasound imaging

D. V. Leonov[1,2]

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Abstract

Ultrasound imaging is routinely used to diagnose and monitor the progression of kidney disease. It supports evaluation of the presence of abnormal formations such as stones, cysts, and tumors, and also the performance of various manipulations under ultrasound guidance. However, the effectiveness of an investigation depends largely on the qualifications of the sonologist. Training using phantoms increases qualifications. This article discusses the creation of a kidney phantom which can be used as a standalone training tool or as part of a more complex phantom, such as a torso model. This phantom is made of a durable material which is not susceptible to drying out or bacteria. It consists of models of the pelvis with Malpighian pyramids and cortex and contains kidney stones and focal formations. The acoustic characteristics of the phantom tissue are in the range of values characteristic of human tissues, namely, the speed of sound and the attenuation coefficient in the cortical layer model are 1530 m/sec and 0.35 dB/cm/MHz. The phantom supports development of skills in assessing the size, shape, and structure of the kidney and those of diagnosing stones and focal formations, and will be useful in advanced training courses for ultrasound diagnostic doctors.

Introduction

Ultrasound is widely used to evaluate kidney disease because it is noninvasive, safe, and suitable for outpatients [1]. It is an effective way of obtaining images of a variety of kidney structures and can be used to evaluate conditions such as renal failure, nephrolithiasis, and hematuria. Important factors in identifying renal abnormalities and predicting renal function include kidney size and cortical thickness [2]. In addition to diagnostic procedures, ultrasound is widely used in minimally invasive surgeries as a navigation aid [3, 4]. As ultrasound imaging is an operator-dependent method, there is a need to train highly qualified physicians.

Medical phantoms are safe and effective training tools which reduce stress and increase confidence when working with patients [5, 6]. Hands-on phantom training improves the competence of sonographers, ultimately reducing risk to patients. There is currently a shortage of high-quality phantoms in training centers, so students and teachers practice by creating their own models for training [7, 8]. The need for phantoms also comes from the fact that many existing phantoms have drawbacks such as susceptibility to drying out, mold, poor anatomical fit, difficulty in manufacturing, inadequacy to the needs of a particular training course, and high cost [9–16].

This article discusses a method for creating a kidney phantom which can be used as a standalone teaching tool or as part of a more complex phantom, such as a torso model. The phantom created in this way is durable, not susceptible to drying out or the appearance of fungi, and is similar to human tissue in terms of acoustic parameters. It supports the development of skills in ultrasound examination of the kidney and the diagnosis of stones and focal formations, as well as the performance of manipulations under ultrasound guidance.

Materials and methods

During the study, the following ultrasound scanners were used: a SonoAce 8000 ExPrime (Medison, South Korea) with an L5-9 EC linear sensor and a Sonomed-500 (Spektromed, RF) with a 7.5L38 sensor, operating at a carrier frequency of 7.5 MHz. The study was carried out in the depth range 3–5 cm. 3D printing was performed on an "X Pro" FDM printer (Picaso, Russian Federation) using PLA plastic.

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✉ D. V. Leonov
strat89@mail.ru

1 Scientific and Practical Clinical Center for Diagnostics and Telemedicine Technologies, Moscow, Russian Federation

2 Moscow Power Engineering Institute, Moscow, Russian Federation

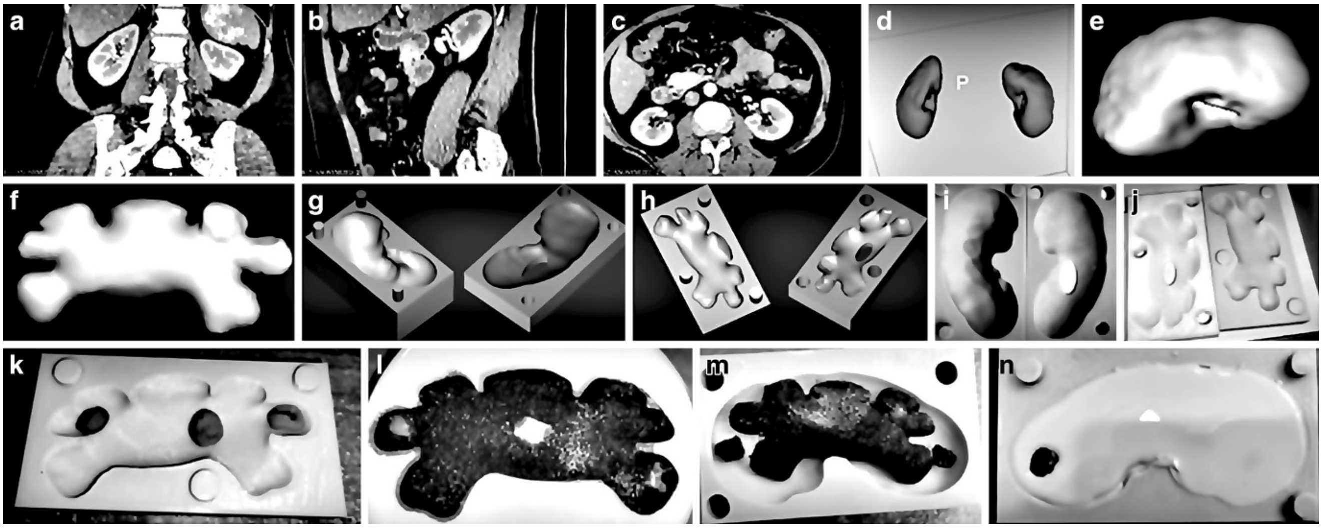

Fig. 1 Illustrations of creation of a kidney phantom: **a**–**c** segmentation of the kidney using computed tomography data of the abdominal region in the frontal (**a**), sagittal (**b**) and horizontal (**c**) planes; **d** volumetric representation of the segmentation result; **e** , **f** results of segmentation of the cortical layer of the kidney (**e**) and pelvis (**f**) in the Meshimixer program; **g** , **h** virtual models of molds for casting a kidney phantom (**g**) and pelvis (**h**); **i** ,**j** models after 3D printing; **k** placement of kidney stones before filling; **l** filling the pelvis; **m** placement of the pelvis and models of focal formations in the kidney; **n** process of filling a kidney phantom

Modeling used an anonymized computed tomogram of the abdominal cavity. The "Slicer 3D" program ("The Slicer Community", USA) was used for segmentation of the kidney, as shown in Fig. 1a–d. The data were then exported in STL format to the Meshmixer program (Autodesk, Japan), where models of two-piece injection molds with pouring holes were created (Fig. 1e–h). The models were transferred to the Polygon X program (Picaso, Russian Federation) to prepare the G-code for 3D printing, and were then printed on a 3D printer. Printing of the forms shown in Fig. 1i, j took 7.5 h. Stones were placed into the pelvis mold and filled with hyperechoic material (Fig. 1k,l). The models of the pelvis and focal formations were then placed in a mold for pouring the kidney and the mold was filled (Fig. 1m, n).

PVC plastisol with different concentrations of graphite powder admixture in the range from 0.5 to 1.5% was used as the main material for creating the phantom. The concentration of admixes affected the echogenicity of tissues on the ultrasound scanner screen. Pelvis tissue was modeled with a material with a hardness of 3 units on the Shore scale, and the renal cortex with a material of hardness 6 units. Two levels of echogenicity were used to create the phantom elements: isoechoic and hyperechoic. An increase in echogenicity was achieved by increasing the concentration of graphite powder admixture.

Results and discussion

Figure 2a shows a kidney phantom created using this technology and demonstrating a high level of anatomical similarity to the simulated organ. Phantom dimensions were $118 \times 45 \times 62$ mm and weight was 173 g. Figure 2b–d show ultrasound images of the phantom. As the phantom was examined outside the torso, a linear sensor designed for superficial organs, operating in pseudo-convex mode to increase the field of view, was used for visualization. It can be noted that the pelvis is modeled by tissues with uniformly increased echogenicity, and the tissues surrounding the pelvis are hypoechoic. Figure 2c shows a kidney stone, which is a hyperechoic interface, behind which an acoustic

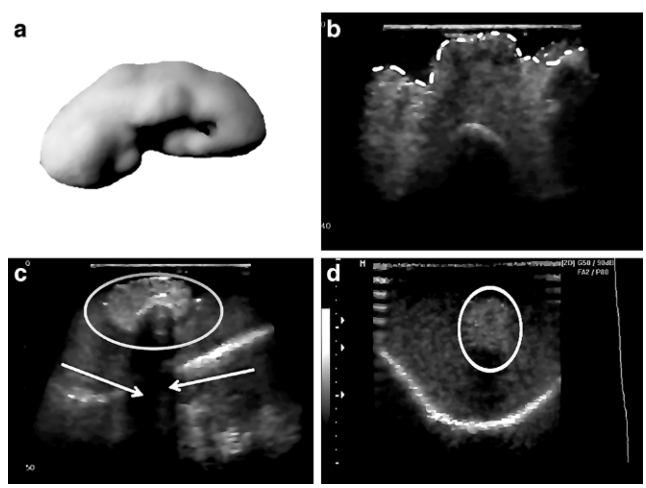

Fig. 2 Illustration of results: **a** appearance of phantom after removal from the injection mold; **b**–**d**) ultrasound images showing the border of the pelvis (**b**), marked with a dashed line, a kidney stone (**c**), creating an acoustic shadow, which is indicated by the arrows, and a hyperechoic focal formation (**d**)

shadow is seen. The width of the shadow is used to estimate the stone size. Size in the image shown is 13 mm. Figure 2d shows an ultrasound image of a tumor model measuring 6 mm. Manufacture of this phantom took 3 h. The phantom can be used repeatedly for visualization; no special storage conditions are required; it can serve for several months without loss of quality [15]. The phantom can also be used as part of a torso model [5], similar to the situation with previously presented models [14]; needles can be inserted into it and manipulations can be carried out under ultrasound guidance.

The speed of sound and the attenuation coefficient in the phantom are 1530 m/sec and 0.35 dB/cm/MHz respectively, corresponding to the values observed in human tissue [17]. The positive qualities of the selected material also include the fact that it can be used to make phantoms for both computed tomography and magnetic resonance imaging [10–12]. Unlike other materials used to create phantoms, such as gelatin and agar-agar [18, 19], the material used here is not susceptible to drying out or the appearance of bacteria and does not require special storage conditions.

The importance of high-quality training of doctors in the field of interventional procedures cannot be overemphasized, as this helps to minimize pain and medical errors [7]. Realistic phantoms have proven valuable in improving the training of physicians, especially in the context of biopsy procedures [8, 20]. By closely mimicking the anatomy and properties of real tissue, these phantoms benefit medical students, residents, and practicing physicians who wish to develop existing and acquire new skills [21]. In addition, the phantom described here may be useful for developers of ultrasound imaging algorithms, for example, for testing algorithms that increase the likelihood of detecting kidney stones [22, 23].

It is of note that this study has a number of limitations. Thus, it does not demonstrate the abilities of technologies involving modeling the procedure for drainage of the renal pelvis, which is one of the most common procedures. In addition, a kidney phantom outside the abdominal cavity is modeled, while greater realism needs addition of models of the rib, skin, muscle tissue, and nearby organs. Another limitation of the model is its inability to reproduce movements of the kidney as the patient breathes, which is typical for real operating rooms. Overcoming these limitations will be possible with further improvements in phantom creation technology.

Conclusions

This article discusses a method for creating a kidney phantom for ultrasound diagnostics which can be useful in training doctors or testing new equipment and imaging algorithms. Use of the phantom creation method described here yields a kidney model which replicates the organ of a specific patient, which can be useful when planning surgical intervention. The material of the phantom corresponds to the tissues of the simulated organ in terms of the speed of sound and the attenuation coefficient. The phantom contains the pelvis, kidney stones, and focal formations and supports practice of diagnostic and ultrasound-guided manipulation skills.

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