Original Article

Fabrication of Low-cost Realistic Three-dimensional Static Kidney Phantom for Ultrasound-guided Biopsy Applications

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Abstract

Background: The rapid growth of using ultrasound-guided interventional procedures, including biopsy and drainage, which considered painful procedures, leads to improving the practice cycle of ultrasound-guided procedures. Fabrication of low-cost tissue-mimicking phantoms that serve as a training tool medium for kidney needle biopsy procedures has dramatically overcome the drawbacks associated with these practices, such as reducing the number of miss lesions, medical errors, and recurrence rate as well as these phantoms are widely available and considered a good substitute for cadavers which were not always available and relativity expensive. However, several drawbacks are associated with current kidney phantom models, mainly the short shelf life and the high fabrication cost. **Methods:** This study aims to fabricate a realistic three-dimensional static mature human kidney phantom from low cost and available material for training on ultrasound-guided interventional procedures mainly biopsy test; the material used to fabricate our model is the gelatin-agar mixture. **Results:** This model proved that it is a tissue-mimicking material by measuring their acoustic properties which nearly the same as real human kidney tissue. **Conclusion:** The results of practicing interventional procedures on our phantom model showed good and easy uses for interventional procedures training as well as make it a preferable and economically affordable model.

Keywords: Interventional radiology, kidney, phantom, renal biopsy, ultrasound

Introduction

Ultrasound-guided needle biopsy is a medical procedure used to explore more about lesions and masses and detect their properties. Ultrasound guidance procedures, including fine needle aspirations, percutaneous biopsy, or catheter insertion, are considered as commonly used practices. Many practices involving needle guides are associated with ultrasound.[1]

The majority of radiologists, once they well practice the technique, tend to perform interventional techniques "freehand." Ultrasonic guidance procedures are considered a hard technique to practice. The first attempt at detecting needles in soft tissue and eventually guiding them into lesions are associated with considerable anxiety and frustration, especially for most trainee radiologists.[2]

Phantoms are anthropomorphic that fabricated to represent a defined anatomical structure. They are designed to use in medical research, training, and quality assurance. Phantom could be made from different materials with different geometric and technical properties based on their application. Alssabbagh *et al*. fabricated a three-dimensional (3D) thyroid gland phantom that could mimic computed tomography (CT) characteristics of real tissue.[3] Opik *et al*. have developed a high fidelity anthropomorphically shaped physical phantom to simulate the liver tissue, which uses with the robotic surgical system organs.[4]

For biopsy test purposes, an ideal phantom should simulate the structural and physiological properties of human tissue and minimize the sideways movement of the needle. Tissue-mimicking phantoms that precisely represent the

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properties of human organs tissue are playing a major role in safety practicing and verification of new imaging procedures.[5]

The wide use of ultrasound-guided interventional procedures, including biopsy and drainage, which considered painful procedures has pushed toward improving the efficiency of the training and the practicing cycle of ultrasound-guided procedures, beginner as medical students and trainees usually used cadaver for practicing ultrasound-guided interventional procedures or by training on real patients. However, practicing these procedures on patients by student and beginner physicians lead to many serious medical errors that could be painful and lethal, so it is not recommended to practicing such procedures on patients.[6]

Today's challenge in kidney needle biopsy training is basically designing a low-cost tissue-mimicking phantom, which can be used more than once to serve as a training tool and practice medium for kidney needle biopsy procedures. Several drawbacks are associated with current kidney phantom models, mainly the short shelf life of these models and the high fabrication cost.

Therefore, this study aims to fabricate a realistic 3D mature static human kidney phantom from low cost and available material; basically, the gelatin-agar mixture, which according to previous studies in the same field, greatly simulates the real kidney tissues.[7] The phantom designed can be used frequently (more than one time). It will be basically used to improve the quality assurance of kidney needle biopsy procedures under ultrasound as well as make it easy for students and trainees practicing the biopsy test widely possible instead of using pricy commercial training phantoms available today.

Materials and Methods

Initial sample preparation

Initially, three samples were prepared and tested under ultrasound to develop the final mixture for phantom fabrication. All three samples were basically consisting of a gelatin-agar mixture but with different concentrations. For the first sample, a 30 g of dry weight gelatin powder (Sigma Aldrich) and 5 g of starch powder were used to prepare the sample; both powders were dissolved in 500 ml of distilled water and boiled to 75°C. The mixture was left to cool down at the normal room temperature and then stored in the fridge under 4°C for 24 h. The second sample consisted of 30 g of dry weight gelatin powder and 9.0 g of dry weight agar powder (Sigma Aldrich) and 5 g of starch. All the materials dissolved in 500 ml of distilled water and heated to 75°C. The mixture was left to cool down at the normal room temperature and then stored in the fridge under 4°C for 24 h.

While for the third sample, 30 g of dry weight gelatin powder and 9.0 g of dry weight agar powder (Sigma Aldrich) were dissolved in 500 ml distilled water and heated to 75°C. The mixture was left to cool down at the normal room temperature and then stored in the refrigerator under 4°C for 24 h [Table 1].

The three samples were tested under ultrasound, to investigate their acoustic properties to determine which sample perfectly simulates the real kidney tissue most under ultrasound. The samples were tested by a 3.5 MHz Convex probe at a scanning angle of 90°. Sensor CASSY-2 from Leybold was used to measure the speed of sound, sound attenuation, and thermal diffusivity; Table 2 shows the values of these measurements for the three samples compared to the value of the same measurements of the real kidney tissue under ultrasound.

Referring to Table 2, it was obvious that the speed of sound, attenuation, and the thermal diffusivity (speed of sound: 1553 m/s, attenuation: 0.47 dB/cm/MHz, and thermal diffusivity: 0.132 mm^2/s) of sample 3 were the closest value of these measurements of the real kidney tissue under ultrasound (speed of sound: 1546 m/s, attenuation: 0.58 dB/cm/MHz, and thermal diffusivity: 0.141 mm^2/s). It is obvious from Table 2 that sample 3 is the sample that mostly has the same acoustic properties as the real renal tissue and thus is considered the sample that best among others to simulate the real kidney tissue under ultrasound; for this reason, sample 3 chosen for the final fabrication of our phantom.

Fabrication of kindy phantom

Designing of 3D kidney mold

For the designing of mature kidney mold, a 3D anthropomorphic kidney with the adrenal gland model made from fiberglass was used to manufacture the kidney phantom shape [Figure 1]. A 1500 ml elastic-plastic container chosen to pour the mold solution; the container was fixed at the center bottom of retort stands; then the 3D kidney model was hanged with the stand using rope, taking into account that the kidney model is adjusted to be at the center of the container with the same distance from all sides [Figure 2].

The mold solution was primarily made of agarose powder ($C_{24}H_{38}O_{19}$)–(Sigma Aldrich). 20 g of dry weighted agarose powder was dissolved in 1500 ml of distilled water. The solution was mixed properly and then heated to 80°C; it was left to cool down for room temperature, then it smoothly poured into the plastic container that contains the kidney model. The container was stored at room temperature (22°C ± 2°C). After 48 h, the mold became solid and flexible; it was ready to eject the 3D kidney anthropomorphic from the mold; the mold's internal lumen of the mold took the same shape, size, and dimension as the kidney anthropomorphic. Figure 3 shows the removal of the kidney anthropomorphic from the mold. After the anthropomorphic has been removed, the mold was ready, the tissue-mimicking solution was prepared in the same concentration, and properties as sample 3, a red dye was added to the solution to make the solution color more realistic. The mold was fixed on a stable flat board. Then, the solution was poured into the mold simultaneously then stored steadily in the refrigerator (4°C) for 48 h. After 48 h, the mold was moved out from the refrigerator, the mold was incised, and the kidney

Table 1: Summarization of the composition of all samples

Sample	Material	Mass (gram)			
Sample one	Gelatin	30g			
	Starch	5g			
Sample two	Gelatin	30g			
	Agar	9g	Dissolved in 500 ml of distilled water	Heated to 75°C	Stored at 4°C for 24 h
	Starch	5g			
Sample three	Gelatin	30g			
	Agar	9g			

Table 2: The acoustic properties of gelatin-agar-starch samples and compare them with the acoustic properties of the real kidney tissue

Property	Sample 1	Sample 2	Sample 3	Real - kidney tissue*
Speed of sound (m/s)	1956±21	1882±10	1553±15	1546
Attenuation (dB/cm/MHz)	0.31±0.05	0.36±0.05	0.47±0.05	0.58
Thermal diffusivity (mm^2/s)	0.220±0.006	0.237±0.004	0.132±0.006	0.141

*According to Insana[8] and Feldman[9]

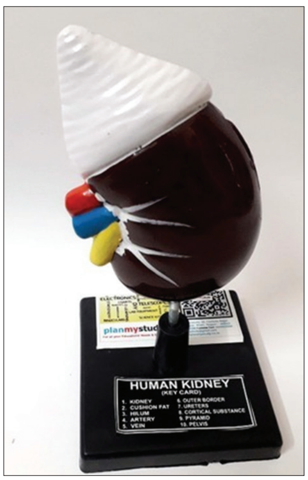

Figure 1: The three-dimensional anthropomorphic kidney model

Figure 2: The preparation steps of pouring the mold material

phantom was gently pulled out. Figure 4 shows the final kidney phantom as it is ejected from the mold.

Renal depth in a mature human was estimated by Xue *et al*., 2017 using a new formula. Renal depths were determined using CT by measuring the distance between the skin and the anterior as well as the posterior surface of the kidneys at the level of the renal hilum. The left kidney depth was found to be 6.82 ± 0.65 cm, while the right kidney depth was 7.03 ± 0.6 cm.[10] The renal depth was taken into account. To make the biopsy practicing more similar to the real renal tissue, the kidney phantom was placed into a gelatin medium at a depth of 7.32 cm from the surface [Figure 5].

Results

Characterization of tissue-phantom model

To produce a kidney tissue mimic material, a mature 3D-kidney model was used to design the kidney mold. Then, the tissue-mimicking solution was poured into the mold and kept in the refrigerator (4°C) for 48 h. After 48 h, the mold has moved out from the fridge. Then, the mold was incised; it was obvious that the tissue-mimicking phantom took the realistic shape and diameter of the 3D Kidney model.

Phantom evaluation under ultrasound

The final phantom was fabricated and tested under ultrasound, a CHISON Doppler ultrasound machine used for this purpose with a 3.5 MHz Convex probe and scanning angle 90°. Figure 6a shows a sagittal image of the final kidney phantom under ultrasound, while Figure 6b shows an axial image of the kidney phantom. Figure 6c shows the Trucut biopsy needle (16-gauge needle) while inserted (45°) in the kidney by the radiologist.

Discussion

Recently, interventional radiology procedures including biopsy and drainage have been considered preferable and minimally invasive procedures since they are more comfortable for the

Figure 3: Removal of kidney model from the anthropomorphic

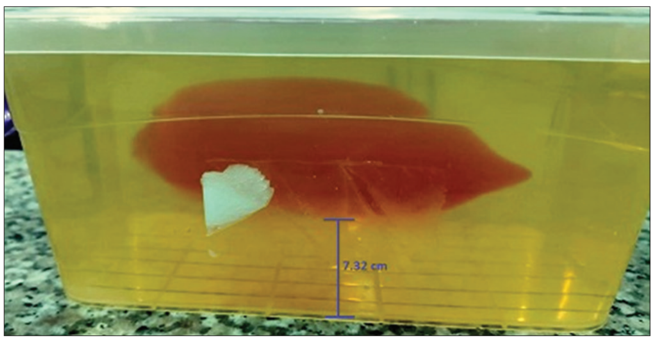

Figure 5: Kidney phantom place in gelatin medium in 7.32 cm depth to simulate real renal depth

patients and have less chance for infections and lower cost compared to other procedures such as surgery.[11]

For interventional procedures, high training will lead to good practicing and high performance, which minimizes the pain and medical errors that may associate with these procedures, such as biopsy when it is applied to patients. Realistic phantoms improved and maintained physicians' skills, which in turn improve the performance and dramatically minimize the missed lesion and enhance the success of biopsy procedures.[12] This makes realistic phantoms that precisely simulate real tissue anatomy and properties an important tool for training and practicing not only for residents but also for medical students.[13]

There are a variety of versions and types of training phantoms for educational and training purposes in medicine. However, the vast majority of these phantoms are comparably costly and include many defects in anatomical structure and have a relativity short life span.[14] In some recent studies, they were basically used nonwater-soluble material for phantom fabrication, including Acrylonitrile–butadiene–styrene[15] and some other acute oral toxic material such as Polyvinyl alcohol.[16] Some other studies presented models that can withstand till 3 months after manufacturing. They did not show signs of deterioration by preserving them in standard conditions.[17]

Figure 4: Final kidney phantom after it has ejected from the mold

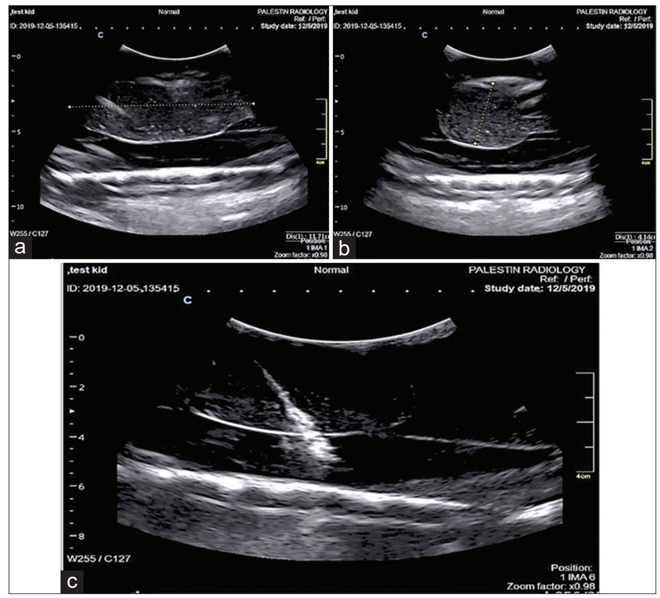

Figure 6: From the left; (a) Shows sagittal image of the final kidney phantom under ultrasound. (b) Shows an axial image of the kidney phantom with the kidney diameter obvious. (c) Shows the Trucut biopsy needle (16-gauge needle) while inserted (45o) in the kidney by the radiologist

In this study, a 3D-realistic kidney phantom made up of relativity low-cost material including gelatin and agar powder was proposed. This model has major advantages; it allows the use of a wide different low-cost, nontoxic, biocompatible materials, and water-soluble material was used to fabricate our phantom. These materials are mimicking human kidney tissues. One unit of this presenting model costs 70 USD, which makes it quite affordable and available for a wide range of educational institutions as well as students and physicians compared to the standard model cost, which starts from 4442 USD according to True Phantom Solution-2020.

The ultrasound images of the kidney phantom of our presented model, as shown in Figure 6a and b, show that the kidney appears clearly and realistic. However, it slightly shortage the internal structure. The kidney medium does not appear similar to the appearance of the real human kidney as various materials were used for fabrication. This is because the surrounding tissue of the human kidney has higher attenuation than the kidney itself, while for the phantom, it is the opposite.[18] The results showed that our phantom model is quite realistic and tissue-mimicking under ultrasound and easy to practicing and training compare to the traditional models. Our proposed model allows creating a low-cost phantom, which can be a good substitute for the expensive commercial training phantoms available today.

Conclusion

This study was presented an economically affordable, realistic static kidney phantom; this phantom appears realistic in ultrasound imaging and has good elasticity. The acoustic properties of our tissue-mimicking material used for phantom fabrication, including speed of sound, attenuation, and thermal diffusivity, were measured and showed a perfect fit of the acoustic properties of the gelatin-agar materials that were used with the acoustic properties of the real human kidney tissue as presented in Table 2. The phantom was tested under ultrasound and appeared clearly with their dimension, as shown in Figure 6a and b. Moreover, it was also tested by radiologists under ultrasound while inserting a Trucut biopsy needle, as shown in Figure 6c.

Our low-cost gelatin phantoms model provides several advantages over other simple models, primary skills including flexible probe positioning, and easy needle placement due to the flat surface of the model enhances practicing learning and provides a convenient way to practice invasive procedures before performing them on live patients.

In addition, our model's main advantage is the ability to use it multiple times. Practicing needle placement on the model can leave some marks and scratch on the gelatin. A proposed technique to increase the shelf life of our model, in particular, is microwaving the model for 7–10 s which will be enough to remove all marks and scratch from the model and reuse it again.

The results of practicing interventional procedures on our phantom model show good and easy uses for interventional procedures training as well as make it a preferable and economically affordable model. The results also provide good feedback for future improvement.

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Conflicts of interest

There are no conflicts of interest.

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