

A training phantom for ultrasound-guided needle insertion and suturing

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ABSTRACT

PURPOSE: During gynecologic brachytherapy (BT), suturing and image-guided needle insertions are highly skill-dependent tasks. Medical residents often have to practice these techniques in the operating room; this is sub-optimal for many reasons. We present a fast and low-cost method of building realistic and disposable gynecologic phantoms, which can be used to train physicians new to gynecologic BT.

METHODS: Phantoms comprised a rectal cavity large enough to accommodate a standard trans-rectal ultrasound (US) probe, a vaginal cavity, a uterus, a uterine canal, and a cervix, all embedded in a gelatin matrix. The uterus was made of gelatin and coated with rubber to mimic the texture of soft tissue and for computed tomography (CT) and US image contrast. The phantom's durability, longevity, construction times, materials costs, CT, and US image quality were recorded. The speed of sound in the gelatin was measured using pulse echo measurements.

RESULTS: Anatomic structures were distinguishable using CT and US. For the first phantom, material costs were under \$200, curing time was approximately 48 hours, and active participation time was 3 hours. Reusable parts allowed for reduction in time and cost for subsequent phantoms: under \$20, 24 hours curing time, and 1 hour active participation time. The speed of sound in the gelatin ranged from 1495 to 1506 m/s.

CONCLUSION: A method for constructing gelatin gynecologic phantoms was developed. It can be used for training in image-guided BT needle insertion, placing a suture on the vaginal wall, and suturing the cervical lip. © 2014 American Brachytherapy Society. Published by Elsevier Inc. All rights reserved.

Keywords:

Gynecological; Brachytherapy; Cervix; Phantom; Training; Suturing; Needle insertion

Introduction

Phantoms are artificial representations of anatomic structures, and they are used in medical research, training, and quality assurance. Depending on their applications, phantoms have different material, geometric, and technological properties. For example, Rice *et al.* built a three-dimensional (3D) head phantom from a material with metabolites that could mimic the MRI characteristics of real tissue (1). Madsen *et al.* designed gelatin phantoms that could be used for heterogeneous elastography because the stiffness of the gelatin could be decreased in regions where safflower oil is added (2–5). Kirby *et al.* studied deformable image registration using a two-dimensional

head and neck phantom constructed from polyurethane (6). To study transperineal needle insertion, Hungr *et al.* designed phantoms that consisted of a rectum and a prostate suspended in a clear and puncturable polyvinyl chloride mixture (7).

Although there are phantoms for many different anatomic regions, an intensive literature search revealed no discussion of construction of an in-house gynecologic phantom (i.e., vaginal cavity, cervix, uterus, rectum). Specifically, there are no gynecologic phantoms that can be constructed in a medical or research laboratory with readily available materials, quickly and cheaply enough for them to be considered disposable. At the clinic, a phantom of this nature would be useful for training medical residents in gynecologic brachytherapy (BT), which requires suturing and the image-guided insertion of needles into the cervix.

Therefore, the purpose of this study was to design and evaluate a gynecologic gelatin phantom to be used for gynecologic BT training. For these purposes, it should be

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transparent to allow external visualization of the suturing process, it should look realistic under computed tomography (CT) and ultrasound (US) imaging, it should have realistic tactile and material properties, and it should be resistant to both usage and storage in addition to the aforementioned useful phantom qualities. Figure 1 shows the phantom with the relevant parts labeled.

This phantom is specialized for training in gynecologic BT procedures such as the transrectal US image-guided insertion of needles, suturing the cervical lip, and placing a suture on the vaginal wall that is meant to secure a BT tandem. Before treating patients in the operating room, medical residents learn these procedures by observing senior physicians. This poses problems: (1) they must observe surgery within a very limited field of view, (2) both procedures require a significant amount of experience, and (3) there are many different anatomies and only a limited number of cases.

For other applications, there are gynecologic phantoms available. Almeida *et al.* presented a design and study of a water-filled gynecologic phantom that could be used in testing treatment planning systems and applicators, dosimetry, and quality assurance (8). This phantom was designed to hold low-dose rate BT applicators in a water-filled housing. It was anatomically correct so that phantom imaging and reconstruction techniques could be more realistically simulated. Nazarnejad *et al.* constructed a gynecologic phantom for inserting the gynecologic applicator that is capable of film dosimetry (9). Film dosimetry was achieved in this phantom because it was composed of soft-tissue mimicking, Plexiglass slabs, which allow it to perform dosimetry for different source points.

Also, there are gynecologic phantoms available commercially. Simulaids, Inc., (Saugerties, NY) produces life-like phantoms that are tailored to train the user in diagnostic gynecologic procedures through anatomic instruction, abdominal

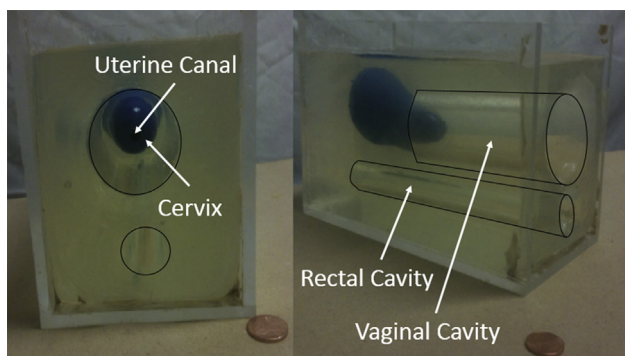


Fig. 1. Gynecologic gelatin phantom. This phantom was designed to be used as a training tool for medical residents in gynecologic brachytherapy. Its puncturable cervix mimics the texture of soft tissue and thus enables its use in transrectal US image-guided needle insertion, suturing of the cervical lip, and placing a suture on the vaginal wall that is meant to secure a BT tandem. Characteristics that were evaluated include the phantom's longevity, durability, and compatibility with various imaging modalities. A U.S. penny is also shown for scale.

palpation, and speculum instruction (10). Gynecologic training phantoms with US compatibility are developed at Blue PhantomT (CAE Healthcare, Sarasota, FL) (11). They provide users with strong US contrast of anatomic structures so they can be used in transvaginal US training. These are also highly life-like phantoms and are designed specifically for obstetrics and US imaging procedures. Many of these commercial phantoms are durable, long-lasting, and cost several thousand dollars.

This gynecologic phantom is unique in that it was designed for our specific training purposes and can be reproduced quickly and economically. It has all the relevant anatomic structures in their respective positions (uterus, cervix, vaginal cavity, uterine canal, and rectum). To mimic the texture of soft tissue, all structures were made with gelatin. The gelatin uterus was coated with rubber to simulate skin.

Methods and materials

The following sections describe the materials and equipment required to build the phantom, the phantom construction process itself, and our evaluation process for the phantom.

Phantom construction

A completed phantom consists of a gelatin matrix, which fills an acrylic enclosure with two open faces: the “front,” toward which the vaginal and rectal cavities open, and the “top,” from which the gelatin is poured. The vaginal and rectal cavities are simulated by cylindrical shafts that run from the front face to the opposite end of the enclosure. The inside-facing end of the vaginal cavity runs flush to the uterus, which is simulated by a pear-shaped gelatin mass. The gelatin uterus is covered by rubber coating to simulate the skin. The following lists the materials and equipment used to construct the phantom.

Materials

2x Acrylic sheet (20.3 cm × 12.7 cm × 0.6 cm).

Acrylic sheet (10.8 cm × 21.0 cm × 0.6 cm).

Acrylic sheet (10.8 cm × 12.7 cm × 0.6 cm).

Acrylic sheet (13 cm × 15 cm × 0.3 cm).

Cylinder (13 mm dia × 18 cm).

Cylinder (6 mm dia × 15 cm).

Cylinder (44 mm dia × 13 cm).

Fast set acrylic bonding agent, SCIGRIPŽ (IPS Corporation, Gardena, CA).

Liquid rubber coating, Performix Co. (Houston, TX).

Industrial grade porcine gelatin, Sigma-Aldrich Corporation (St. Louis, MO).

Clay.

Plastic wrap.

Water (2 L).

70% Ethanol solution.

Equipment

Drill.

Refrigerator.

Electric stove or similar heating source.

C-clamps (size/s).

Computer-aided design (CAD) software*.

3D printer*.

Stirring spatula.

2 L pot.

Thermometer.

*Optional.

The following construction description is intentionally verbose to facilitate repeatability of the process. The phantom construction procedure consisted of (1) vaginal cavity and uterus preparation, (2) housing assembly, (3) gelatin preparation, and (4) phantom assembly. These steps are described in detail in the following paragraphs.

The vaginal cavity started as a positive mold. Later, the vaginal cavity positive was removed from the phantom to produce the vaginal cavity. The uterus starts as a negative mold, which will later be filled with gelatin to make the

uterus positive. Because the vaginal cavity and uterus must be flush together, their geometries were designed together using a CAD software called Inventor 2013 (Autodesk, Inc., San Rafael, CA). The size and shape of the uterus and vaginal cavity dimensions were specified by a brachytherapist to simulate a typical anatomic case. Specifically, the vaginal cavity positive was designed as a 4.4 cm diameter by 13 cm length cylinder (the vaginal cavity itself does not have to be this long; later steps will show that 13 cm is an upper bound, and the length of the vaginal cavity is adjustable). The uterus was designed as a pear shape: 8.2 cm long, 4.8 cm wide at its widest section, and 2.6 cm wide near the cervix. In the CAD software, the uterus was placed in an antverted position relative to the vaginal cylinder, its correct anatomic configuration, and the intersection volume was subtracted from the vaginal cylinder. This process is shown in Fig. 2.

Once the vaginal positive and the uterus negative were designed, they were exported to Standard Tessellation Language (STL) files and 3D printed using a Z-Printer 150 3D printer and ZP 150 High Performance composite printing material (3D Systems; Circle Rock Hill, SC). After printing, both parts were placed in an 8°C refrigerator to expedite later steps in the construction process. 3D printing services, which allow for submission of designs and will ship the finished product (with a turnaround of a few days), are available online (12–14). So, direct access to a 3D printer is not necessary for constructing these phantoms. Also, these parts only need to be created once and can be reused for subsequent phantoms (unless several phantoms are to be made once). The STL files used for this project are freely available for download if a request is made via e-mail.

Then the uterus mold was used to make the gelatin uterus (Fig. 3). Industrial grade porcine gelatin was used to prepare a gelatin mixture to fill the uterus volume. For every 100 mL of room temperature water, 12 g of gelatin powder was gradually stirred into the water. The mixture was heated to 50°C over 10 minutes with constant stirring. Before the gelatin mixture was poured through the hole of the uterus mold, C-clamps were used to secure the two halves of the uterus mold together. After pouring the gelatin

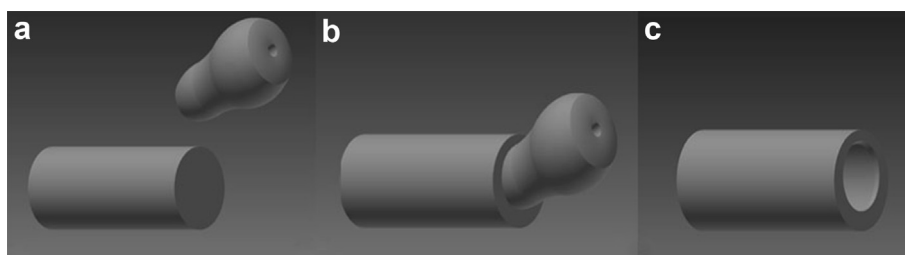


Fig. 2. An illustration of the CAD technique used to create the uterus and vaginal cavity. (a) A virtual, hollow cylindrical shell and a virtual uterus were designed. (b) These were made to overlap such that the uterus had an anatomically correct depth and angle with respect to the vaginal cylinder. Once they overlapped, a common CAD technique called “subtraction” was carried out. Here, the uterus, and any volume it was overlapping with, disappears. (c) After, the subtraction was carried out. Now, if this new vaginal cylinder and the old uterus are printed, they will have matching geometries. CAD = computer-aided design.

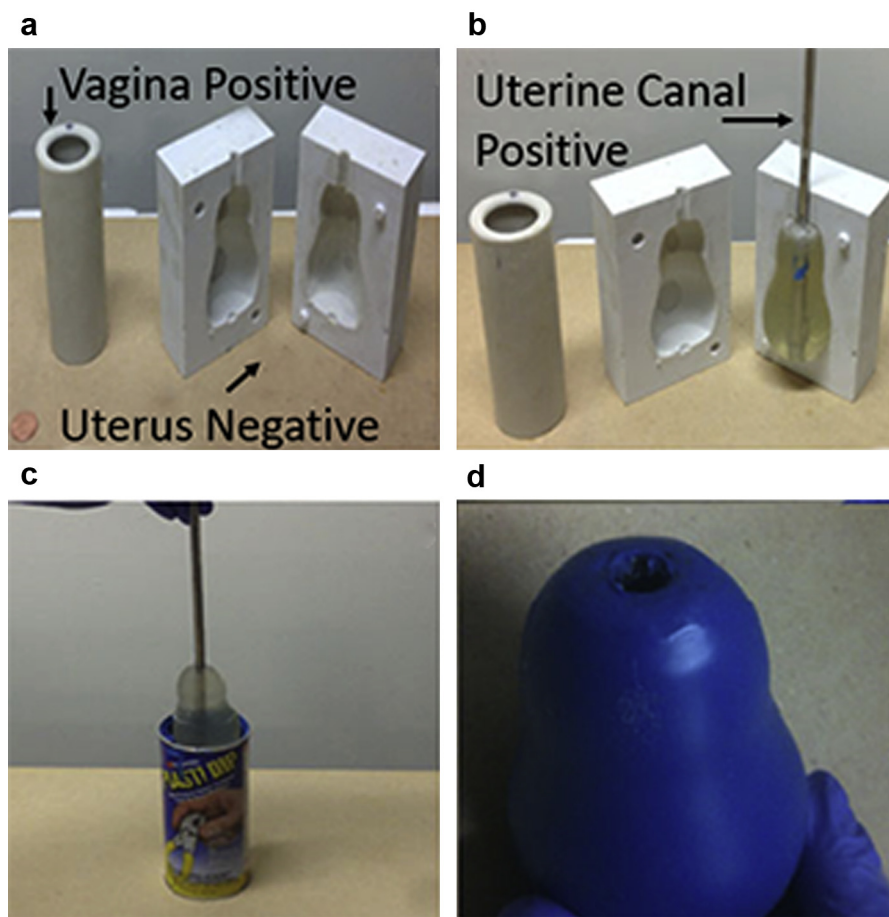


Fig. 3. A series of images depicting how the rubber-coated gelatin uterus was constructed. (a) The 3D printed uterus negative and vagina positive. (b) The 3D printed parts after the uterus mold was used to make the gelatin uterus. (c) The rod used to make the uterine canal being used to dip the gelatin uterus into liquid rubber. (d) After the liquid rubber cured on the surface, the rod was removed and the rubber-coated gelatin uterus was complete. 3D = three-dimensional.

into the mold, the 6 mm (diameter) rod was passed through the hole so that it could act as a positive for the uterine canal (note that smaller diameters can be used if preferred). The set up was allowed to sit for 30 minutes so that the C-clamps were no longer necessary; it was then placed in the refrigerator to expedite the solidifying process. After 4 hours, the gelatin uterus was removed from the mold (with the rod still in place).

Once the gelatin uterus was removed, the rod was used as a handle to submerge the uterus in liquid rubber to give it an outer skin that would provide US and CT contrast. The outer skin also helps keep the gelatin of the uterus from melting in later steps and increases the longevity of the gelatin uterus. The uterus was allowed to hang for 1 hour before being placed in a refrigerator to expedite the solidifying process (note that more layers of rubber can be used to make the cervical surface tougher).

Next, the phantom housing was constructed from five acrylic sheets. Each side is labeled in Fig. 4. Sides 1–4 were sealed together using acrylic bonding agent. Side 5 was designed as a removable wall. Before securing Side 5 to the others, two circular holes were drilled into it with diameters

4.4 cm and 1.3 cm, respectively, to allow passage of the vaginal cylinder positive and 1.3 cm rod, respectively. Both holes were centered along the bottom edge of the removable wall; the centers of the 1.3 cm and 4.4 cm hole were located 3.5 cm and 8 cm from the bottom edge, respectively. The vaginal cylinder and the 1.3 cm diameter cylinder were then passed through their respective holes in Side 5. The edges between both cylinders and the removable wall were sealed with clay. The seal should be as water tight as possible. Similarly, the vaginal cylinder was attached. The removable wall was then held against the foundation with the C-clamps and its edges were then sealed with clay. An image of the set up is illustrated in Fig. 5. The cylinders were manually supported in position until the gelatin was poured, and they could then be supported from the buoyancy of the gelatin. The uterus was then inserted into the vaginal cylinder in an antverted fashion. The fit should be tight enough such that the uterus can stay in place.

Two liters of gelatin mixture were then prepared with the same proportions as for the uterus. The mixture was poured into the phantom housing until the uterus was completely submerged. The phantom was left at room temperature

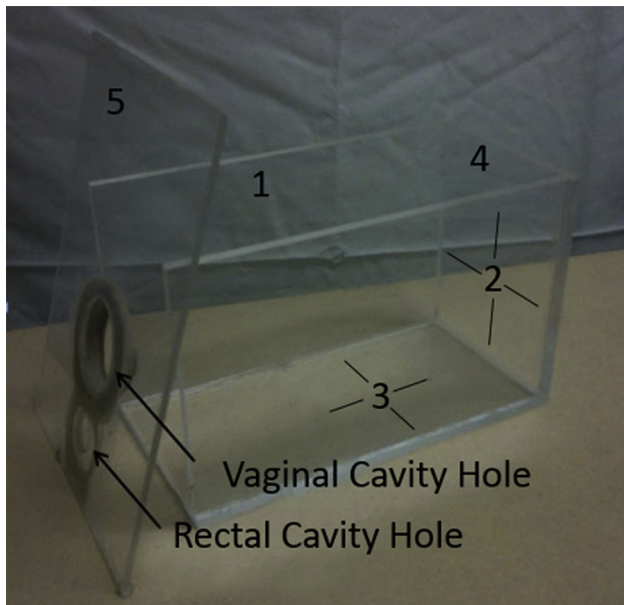


Fig. 4. Four acrylic sheets (labeled 1, 2, 3, and 4) were sealed, with acrylic bonding agent, to make the housing that will encase the gelatin phantom. Acrylic sheet (5) had two holes drilled into it. The positive molds for the rectal and vaginal cavities will be passed through the holes and the sheet will then be secured against the housing.

for 4 hours before the clamps were removed and the phantom was placed in the refrigerator. After solidifying in the refrigerator, Side 5 was removed, followed by the two cylinders. To remove the cylinders, they were gyrated repeatedly (note that it was helpful to place a few drops of water in between the cylinders and the gelatin when removing them to diminish adhesion between the cylinders and the gelatin matrix). This is when the phantom construction was complete and the phantom looked like Fig. 1.

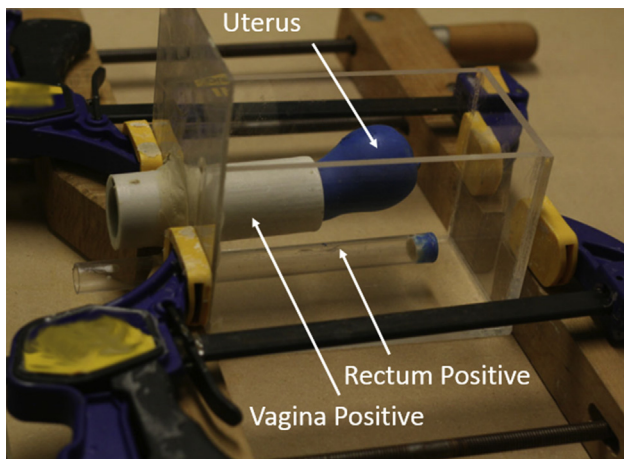


Fig. 5. The set up before liquid gelatin was poured into the phantom housing. Junctions between the fifth acrylic sheet and the vagina positive, rectum positive, and the phantom housing have been sealed with clay. C-clamps are used to further prevent leaks. The uterus fit into to the posterior hole of the vaginal cylinder as the design intended, in an antverted position.

Phantom evaluation

The phantom was scanned using a SOMATOM Sensation spiral CT (120 kVp) (Siemens AG, Munich, Germany) and using a 2102 Hawk EXL transrectal US probe (BK Medical, Herley, Denmark). A qualitative assessment was made of the contrast between the uterus and uterine canal and the uterus and gelatin matrix.

Phantom longevity was determined by storing it in the refrigerator until it was unusable, which we defined as 2 mm of gelatin liquefaction on any of the phantom surfaces. The phantom was checked daily for this condition. To offset desiccation and bacterial degradation of the gelatin, the phantom was stored in a particular way. When the phantom was ready to be stored, the two cylinders were sprayed with 70% ethanol and, after they dried, were placed back into their corresponding cavities. The phantom was then wrapped with plastic wrap and placed it in an 8°C refrigerator. To increase longevity, a parallel study was conducted with 2 mg of thimerosal (antiseptic/antifungal agent) added for every 1 mL of liquid gelatin. Note that thimerosal is rated as a Level 3 health hazard according to NFPA704, but may be worthwhile if longevity is important.

The durability of the rectal wall was evaluated by inserting and removing a transrectal US probe 50 times. US lube was used. A qualitative assessment of the damage to rectal wall was made by checking for fissures and changes in the texture of the gelatin. The durability of the cervix was evaluated by puncturing it 20 times with suturing needles. A qualitative assessment was made by checking for any type of change in texture when punctured.

The speed of sound in the gelatin was measured using pulse echo measurements in water. A sample of cured gelatin was placed between two planar US transducers at a fixed distance of 67 mm (center frequency = 4.5 MHz). This set-up was placed inside a water tank containing degassed and deionized water at 21.5°C. The sample was pulsed using a 500 PR pulser (Panametrics Inc, Waltham, MA), where one transducer transmitted pulses and the other was a passive receiver. The analog input from the transducer was displayed on an externally triggered 54600A oscilloscope (Hewlett Packard, Palo Alto, CA) that had its display set to 1 V/div on the vertical axis and 200 ns/div on the horizontal axis. Thus, the time interval between signal generation and reception of the US wave was measured for a sample of water and gelatin samples 5, 15, and 20 mm thick.

Results

The uterus negative and vagina positive were designed in approximately 2 hours, and 3D printing took 5 hours. The phantom housing took under 10 minutes to construct and 3 hours to cure. The preparation of the gelatin uterus took 0.25 hours of active participation time; it took 10 hours total when the curing times associated with the gelatin and the rubber are included. The curing of the

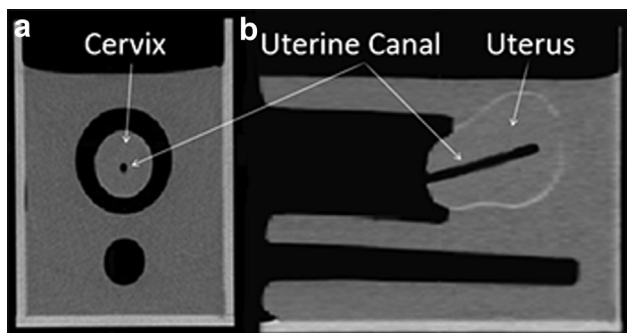


Fig. 6. CT images of the phantom. (a) Axial cross-section shows contrast between the cervix and the uterine canal. (b) Sagittal cross-section shows contrast between the uterus and the surrounding matrix.

gelatin matrix that filled the phantom housing took 14 hours with 0.5 hours active participation time. In summary, construction of first phantom from scratch took approximately 3 hours of active participation time and 2 days including all the curing times. As the phantom foundation, uterus negative and vaginal cylinder can be reused, the time of assembly of subsequently constructed phantoms was primarily constrained by the curing time of the gelatin matrix. Therefore, following phantoms were constructed in about 1 hour of active participation time and 24 hours of curing time.

The material cost for the 3D printing was under \$200. This was the significant component of the total cost. Because the 3D printed parts and phantom housing are reused, material costs for subsequent phantoms was reduced to under \$20.

Figure 6 shows a CT image of the phantom. Figure 6a shows contrast between the cervix and the uterine canal. The contrast between the uterus and the surrounding matrix is depicted in Fig. 6b. In Fig. 7a, a transrectal-US probe is being used to help guide a BT needle into the uterus. The BT needles are represented by the bright spots in Fig. 7b. Figure 8 shows a suturing needle seen through the gelatin matrix.

The phantom lasted 2 weeks in refrigerated 8°C storage. The addition of thimerosal extended the lifetime to 6

weeks. After 50 prodings of the rectal wall, no sign of degradation was observed. After 20 insertions on the suturing needle, there was a slight softening in texture of the phantom cervix. The speed of sound measured in gelatin (range 1495–1506 m/s) was comparable with the speed of sound in water (1463 m/s).

Discussion

This phantom can be built without CAD software or a 3D printer. The STL files are freely available upon e-mail request to any of the first three authors. There are also online services that can have the parts printed and shipped. Some examples are ColorJet Printing, Grow It 3D Printing, and Solid Concepts Inc (12–14). As another option, the vaginal cylinder and the uterus can be made with most types of sturdy pottery clay and traditional molding techniques.

The phantom was used by an attending BT physician and co-author, IH, to demonstrate gynecologic suturing and BT needle insertion to medical residents. The physicians described suturing the phantoms cervical lip to be very similar to the real case as the texture of the phantom cervix strongly resembled that of a human's. However, they noticed the gelatin that was not coated with rubber (e.g., the walls of the phantom vagina) tears easier than human tissue. Moreover, there was less uterine motion during bimanual examinations on the phantom than in real cases.

Some parameters can be adjusted (between phantoms) to fit the user's need. For example, anatomically reasonable modifications to the length of the vaginal cavity, radius of the uterine canal, and the angle between the uterus (axis parallel to uterine canal) and the vaginal cavity (axis parallel to length of cavity) should be trivial. Also, the concentration of gelatin and/or materials other than gelatin can be used for the phantom matrix. This phantom was made with gelatin because it resembled the texture of our intended tissues and was readily available at low cost. A downside to using gelatin is that after inserting and removing BT needles, the needle tracks are visible on subsequent US scans.

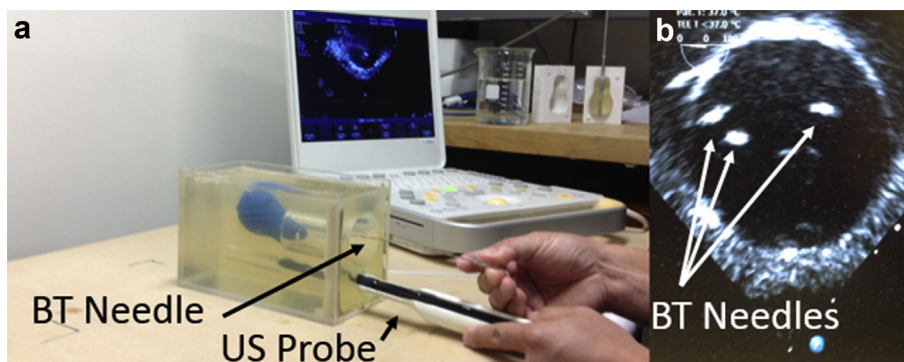


Fig. 7. (a) An attending brachytherapy physician using a transrectal US probe to help guide a BT needle into the uterus. (b) Axial cross-section of uterus taken with a transrectal US probe. The BT needles show up as bright spots on the US. The uterine wall is also distinguishable. US = ultrasound; BT = brachytherapy.

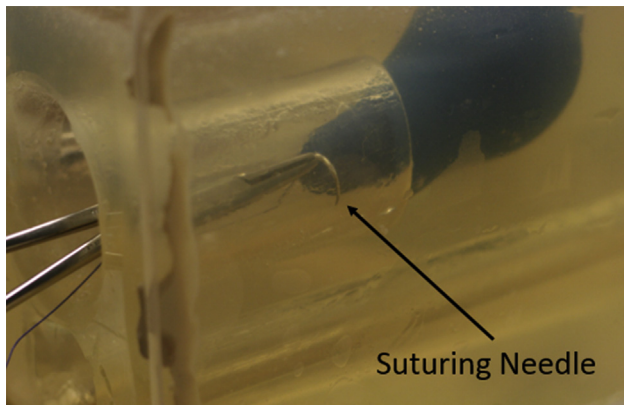


Fig. 8. A suturing needle seen through the wall of the phantom. As one of the main issues in gynecologic BT training is how hard it is to observe the procedures, the transparency in the gelatin may be a useful characteristic. Here, the attending brachytherapy physician is about to show a medical resident how suturing is performed on the cervix.

Future endeavors include using phantoms for preliminary studies on new image-guided treatments and preparing the phantom for multi-modality treatment planning. Experiments will include quantitatively determining material properties and adjusting accordingly to achieve optimal contrast in CT and/or US imaging. Such properties include acoustic and x-ray attenuation coefficients, propagation speeds, and backscatter.

Conclusion

A method and recipe for constructing GYN phantoms was produced. These phantoms consist of a vaginal cavity, rectal cavity, and gelatin uterus, all suspended in a gelatin matrix. They can be made quickly, with low cost, and with basic laboratory equipment. CT and transrectal US images show a strong contrast between the anatomic structures. Medical residents confirmed that the procedures with the phantom were realistic, the phantom helped increase their skills in GYN BT, and that they felt more comfortable in the operating room after using the phantom.

Acknowledgments

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