Investigating Suitability of Different In-House Phantom Materials for Quantification of Transrectal Ultrasound Needle Fidelity for HDR Interstitial Brachytherapy

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Abstract

Purpose: To investigate the suitability of three different materials as background media for use with in-house phantoms for HDR interstitial brachytherapy. In-house phantoms are designed to supplement commercial phantom capabilities and enable interstitial needle placement for needle fidelity determinations. Material considerations included ease of use, fiducial visibility, and geometric fidelity.

Methods: 3D-printed phantoms incorporating seven nylon monofilament string fiducials arranged at fixed distances (60 mm lateral, 40 mm axial separation between outer strings), and an opening for a transrectal ultrasound probe, were fabricated and filled with one of three different materials: liquid water, agar, or a synthetic medical gel (SimuGel #3, Humimic Medical). Each phantom was imaged using 2D and 3D transrectal ultrasound (TRUS) and distances between the outer fiducials were measured and compared to designed values. The agar phantom was imaged at two temperatures (19.8°C and 8.5°C), while the other phantoms were imaged at room temperature.

Results: Room temperature agar demonstrated the highest geometric fidelity, with all but the most proximal lateral 3D US measurement meeting TG-128 tolerances (3 mm lateral, 2 mm axial). Room temperature water was more challenging to work with due to the need to seal the opening for the TRUS probe and exhibited poor resolution, with fiducials appearing as wide streaks. The synthetic gel provides durability advantages since it is shelf-stable and reusable, but exhibited the worst geometric fidelity with all measurements at or exceeding tolerance (2.0-9.3mm) due to the manufacturer reported 1458.85 m/s speed of sound being significantly lower than the fixed 1540 m/s setting of the clinical ultrasound.

Conclusion: Of the materials tested, room temperature agar was the most suitable for achieving geometric fidelity with a clinical ultrasound system. Although agar's limited shelf life can be extended with refrigeration, it is important to image the phantom at higher temperatures for needle fidelity measurements.

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Introduction

Interstitial HDR Brachytherapy includes insertion of needles into human tissue for radiation delivery, often guided by transrectal ultrasound (TRUS)[1]. Quality assurance of TRUS imaging must be performed to ensure that needle positions are well visualized and accurate. While there are commercial phantoms available for TRUS imaging QA, there are limited phantom options that allow needle insertion to quantify needle fidelity and placement accuracy[2]. The purpose of this work was to investigate background media effects on needle visualization and distance accuracy.

Methods

An in-house TRUS QA phantom was designed and 3D printed that included a transrectal opening for the TRUS probe centered at the bottom of the box. Two 3D printed struts were designed to position seven 1 mm-diameter microfilament nylon fiducial strings in an N-shape spaced 30 mm apart laterally, and 20 mm apart axially in reference to the transverse plane. The fiducials were positioned to appear as dots in the transverse plane and lines in the sagittal plane[3]. The phantom was filled with various background formulations to measure the fiducial distances and compare these measurements to the expected values of 60 mm in the lateral direction, and 40 mm in the axial direction (for outer string fiducial spacing). These formulations included water, synthetic medical gel (SimuGel #3, Humimic Medical), and various concentrations of distilled water, agar-agar powder, cellulose powder, and glycerol, at refrigerated and room temperatures[4].

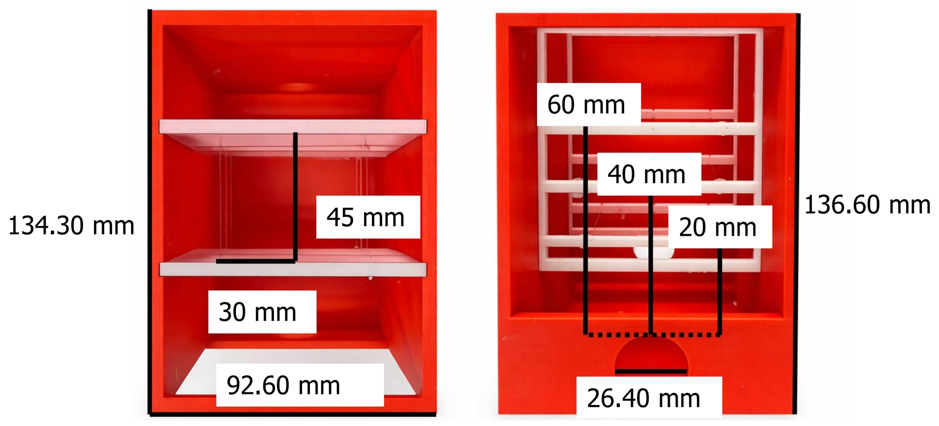

Figure 1: Schematic view of in-house phantom box design in the coronal and transverse planes, showing fiducial dimensions.

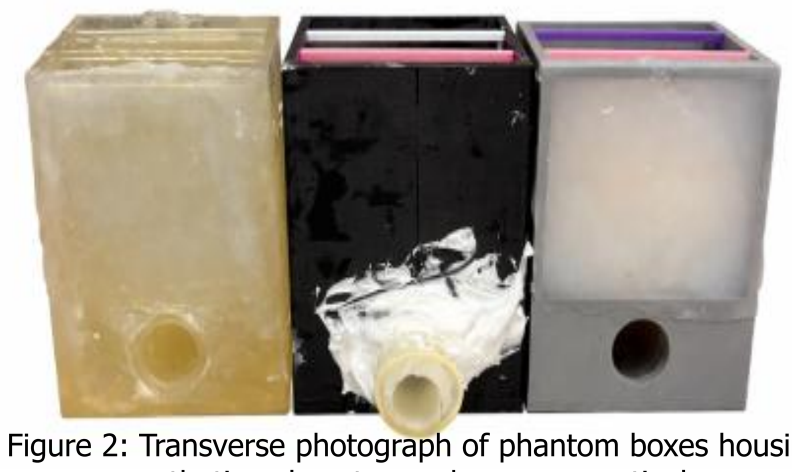

Figure 2: Transverse photograph of phantom boxes housing synthetic gel, water, and agar, respectively.

Table 1: Weighted compositions of TMM's used for 2D and 3D US measurements.

Media	Weight Composition
Water	100% Water
Synthetic Gel	100% SimuGel #3 (Humimic Medical)
Agar #1	70 g Agar-agar powder (3.04%), 30g Cellulose powder (1.30%), 2.2 L Distilled water (95.66%)
Agar #2	70 g Agar-agar powder (2.98%), 30 g Cellulose powder (1.28%), 40 mL Glycerol (2.14%), 2.2 L Distilled water (93.60%)
Agar #3	70 g Agar-agar powder (2.80 %), 30 g Cellulose powder (1.20%), 160 mL Glycerol (8.06%), 2.2 L Distilled water (87.94%)

For water and the agar formulations, the box was 3D printed in PLA, due to its ready availability and low cost. The water phantom included a silicone tube for positioning of the US probe with a cutout in the imaging region to mitigate impact of the silicone wall on acquired images. The silicone tube was placed inside a US cover and secured against the outer walls with heavy-duty silicone to keep a water-tight seal. For the synthetic gel, the medium must be annealed at high temperatures that PLA cannot withstand without warping. Therefore, the box for the synthetic gel phantom was 3D printed with High Temp Resin (Formlabs). The support struts for the agar and synthetic gel boxes were also printed with High Temp Resin to minimize warping. The phantoms were imaged with a bkSpecto E14CL4b endocavity biplance transducer (GE HealthCare) to analyze image quality and spatial resolution, and to measure lateral and axial fiducial distances. 2D image analysis was performed in the transverse plane. 3D TRUS images were generated from a sweep of sagittal images using the Artemis system (Eigen Health) and uploaded into Eclipse (Varian) for analysis. The transverse plane utilized for analysis was taken at the middle of the string in reference to the sagittal plane to reduce variability from string warping.

Figure 3: 3D US transverse-plane scans of water, synthetic gel, and agar formulation #3, respectively, utilized for fiducial distance measurements and spatial resolution/image quality analysis.

Results

Water displayed the worst spatial resolution and image quality, with fiducials appearing as long, white streaks and many artifacts existing in the background. The synthetic gel's stability and extended shelf life are advantageous, but the gel demonstrated the worst distance scaling and a very dark background with little speckle visibility. The third agar formulation provided the best image quality, displaying fiducials as distinct dots with improved contrast while all distance measurements were within 2 mm of expected values at room temperature.

Table 2: Average lateral and axial distance measurements of TMMs from 2D and 3D US scans. Cell colors indicate deviation from expected values: green (<1 mm), yellow (1–2 mm), orange (2–3 mm), and red (>3 mm).

Background	2D Average Lateral Distance (Expected: 60 mm)	2D Average Axial Distance (Expected: 40 mm)	3D Average Lateral Distance (Expected: 60 mm)	3D Average Axial Distance (Expected: 40 mm)
Water	61.67 ± 0.10	41.82 ± 0.10	62.77 ± 0.25	42.15 ± 0.05
Synthetic gel	65.90 ± 0.06	42.00 ± 0.00	67.90 ± 1.10	42.55 ± 0.15
Agar #1 (9.5°C for 2D, 8.5°C for 3D)	63.89 ± 0.19	42.30 ± 0.14	64.90 ± 1.21	42.50 ± 0.30
Agar #1 (19.0°C)	61.49 ± 0.56	40.46 ± 0.07	63.07 ± 0.84	40.85 ± 0.15
Agar #2 (7.7°C)	64.44 ± 0.23	42.15 ± 0.28	65.20 ± 0.82	42.70 ± 0.30
Agar #2 (19.8°C)	61.61 ± 0.23	40.46 ± 0.32	63.07 ± 0.94	41.15 ± 0.15
Agar #3 (10.2°C)	62.62 ± 0.26	40.64 ± 0.00	62.43 ± 0.70	41.05 ± 0.05
Agar #3 (20.2°C)	60.42 ± 0.58	39.53 ± 0.10	61.87 ± 1.20	39.95 ± 0.25

All agar formulations demonstrated improved distance accuracies at warmer temperatures due to temperature dependence of speed of sound in a medium[6]. In most scans, the lateral distances were larger for more proximal measurements, and the 3D scans demonstrated longer distance values than 2D. After noting those discrepancies, the 3D US system's distance from the center of rotation to the transducer's surface was recalibrated. The synthetic gel and agar #3 at room temperature were imaged again after recalibration, with extra US gel added to the phantom to ensure uniform contact against the media's surface. Both formulations underwent improved scan uniformity, with smaller standard deviations across all measurements. The synthetic gel also exhibited lateral and axial distances closer to the expected values, although the lateral distances still exceeded tolerance.

Table 3: Lateral and axial distance measurements of synthetic gel and agar #3 at room temperature from 2D and 3D US scans after recalibration. Cell colors indicate deviation from expected values: green (<1 mm), yellow (1–2 mm), orange (2–3 mm), and red (>3 mm).

	Lateral Distances (Expected: 60 mm)				Axial Distances (Expected: 40 mm)			
Background	2D Proximal	2D Distal	3D Proximal	3D Distal	2D Left	2D Right	3D Left	3D Right
Synthetic gel (Before Calibration)	65.80	65.93	69.30	66.60	42.00	42.00	42.70	42.40
Synthetic gel (After Calibration)	63.82	63.95	65.40	65.30	41.91	41.23	41.60	41.30
Agar #3 (Before Calibration)	60.82	59.60	63.20	60.30	39.43	39.63	40.50	40.30
Agar #3 (After Calibration)	60.55	60.29	61.60	61.00	40.00	40.10	40.10	40.50

Discussion

Of the media tested, room temperature agar #3 was the most suitable for achieving geometric fidelity with a clinical US system. Adjusting the glycerol content can improve the measured results. Although agar's limited shelf life can be extended with refrigeration, the phantom must be imaged at room temperature to increase the speed of sound. Appropriate transducer calibration and uniform probe contact with the phantom's surface are also essential for accurate distance measurements.

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