An investigation of industrial molding compounds for use in 3D ultrasound, MRI, and CT imaging phantoms

Bryan E. Yunker^{a)}

Department of Bioengineering, University of Colorado, Denver, Colorado 80045

Dietmar Cordes, Ann L. Scherzinger, and Gerald D. Dodd

Department of Radiology, University of Colorado Hospital, Denver, Colorado 80045

Robin Shandas

Department of Bioengineering, University of Colorado, Denver, Colorado 80045

Yusheng Feng

Department of Mechanical Engineering, University of Texas – San Antonio, San Antonio, Texas 78249

Kendall S. Hunter

Department of Bioengineering, University of Colorado, Denver, Colorado 80045

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Purpose: This study investigated the ultrasound, MRI, and CT imaging characteristics of several industrial casting and molding compounds as a precursor to the future development of durable and anatomically correct flow phantoms.

Methods: A set of usability and performance criteria was established for a proposed phantom design capable of supporting liquid flow during imaging. A literature search was conducted to identify the materials and methods previously used in phantom fabrication. A database of human tissue and casting material properties was compiled to facilitate the selection of appropriate materials for testing. Several industrial casting materials were selected, procured, and used to fabricate test samples that were imaged with ultrasound, MRI, and CT.

Results: Five silicones and one polyurethane were selected for testing. Samples of all materials were successfully fabricated. All imaging modalities were able to discriminate between the materials tested. Ultrasound testing showed that three of the silicones could be imaged to a depth of at least 2.5 cm (1 in.). The RP-6400 polyurethane exhibited excellent contrast and edge detail for MRI phantoms and appears to be an excellent water reference for CT applications. The 10T and 27T silicones appear to be usable water references for MRI imaging.

Conclusions: Based on study data and the stated selection criteria, the P-4 silicone provided sufficient material contrast to water and edge detail for use across all imaging modalities with the benefits of availability, low cost, dimensional stability, nontoxic, nonflammable, durable, cleanable, and optical clarity. The physical and imaging differences of the materials documented in this study may be useful for other applications. © 2013 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4802083>]

Key words: imaging, phantom, ultrasound, MRI, CT

I. PURPOSE

This study investigated industrial casting and molding compounds for use in a proposed hepatic flow phantom design for ultrasound, MRI, and CT imaging. Many of the phantoms cited in literature are for “static” applications^{1–5} that do not involve flowing fluids even if the phantom contains a fluid as a contrast or a calibration reference. Examples of static phantom types and their applications would be: solid phantoms imitating tissue layer density changes for needle stick training; agar or polymer filled phantoms used for ultrasound training or calibration; water or contrast filled acrylic cylinders used for MRI/CT scanner calibration. The study of blood flow through organs and vasculature requires the use of “flow” phantoms^{6–8} that can accommodate the “dynamic” flows and pressures of fluids such as water/contrast/glycerol mixtures or

blood. The ability to move a flow phantom between imaging modalities enables comparative assessment of each technology’s ability to image and quantify flow against a common physical reference. As a flow phantom must provide a geometrically accurate 3D image of the fluid flow and allow accurate measurement of fluid velocity, the desired properties of a candidate casting material are low image distortion, sharp vessel edge definition, and high contrast between the fluid and the material.

II. METHODS

II.A. Target application

The following proposed flow phantom design was used to select candidate materials from the hundreds of industrial

casting products available. The dimensions of the flow phantom were set to $10 \times 10 \times 10$ cm (1000 cc) (1 l) (61 in.³) to accommodate 3D imaging of the first three portal vein branches of a full scale Caucasian male liver. The flow phantom would be connected to inlet and outlet hoses to establish fluid flow through the phantom while the phantom rested on a laboratory table for ultrasound imaging, or, on the patient beds of MRI or CT systems.

Desired flow phantom material properties included: low cost, easily obtained, nontoxic for ease of fabrication and handling, and nonflammable in raw or cured form. Physical and dimensional stability over physiological and imaging suite temperatures (18/26 °C) (65/80 °F) and physiological fluid pressures (120 mm Hg) (2.3 psi) was desired to maintain an accurate shape of the vascular cavities to ensure repeatable flow data over a six month study. A flexible material was desired to allow repeated insertion of barbed tubing connections without cracking. Easy cleaning was desired to prevent build-up of contrast/glycerol films or blood residues. Materials which are chemically and biologically inert were desired so that the phantom would not degrade or decompose over time when exposed to sunlight, temperature, or the stated fluids. Optical clarity was desired for observing and resolving air bubble issues in the casting processes, finished casting body, and fluid flow during testing, as well as viewing of the cast anatomy for training purposes. Manufacturer's specifications and handling observations during testing were used to screen and evaluate the properties not explicitly tested in this study phase.

II.B. Literature search

While usable 3D flow calibration can be achieved using materials with no anthropomorphic properties, this study focused on materials with densities near human tissue to acquire data that might be useful to future studies simulating human tissue properties with or without flow. Density was chosen as it was a property commonly reported in both manufacturer data and medical tissue literature. A database of tissue and casting compound properties was compiled from the references below.

II.C. Materials selection and fabrication

Several materials were selected against the desired properties for the proposed flow phantom design. Two test samples of each selected material were fabricated in accordance with the manufacturer's instructions. One sample of each material was molded or drilled to create vertical and diagonal contrast wells into which imaging modality appropriate contrast materials such as wood, metal, or water could be inserted or injected. The other sample was fabricated as a solid casting with no internal cavities.

II.D. Ultrasound testing

A Philips (Philips Healthcare, Andover, MA) iU22 ultrasound system was used to test the materials for use in the

proposed flow phantom design. The samples were tested in a deionized water bath in front of a Philips V6-2 (2–6 MHz) 3D curvilinear transducer. The transducer was protected with a thin plastic film as a water seal and acoustic gel was used under the plastic film to improve coupling. Soft wooden sticks with rough surfaces were inserted into the contrast wells of the samples to simulate the diffuse reflections obtained from powdered cornstarch which is commonly used as a contrast medium in water based ultrasound flow testing. Cornstarch was not used as contrast in the sample wells since it settles out of solution quickly, causing a loss of target reflectivity over time. The wooden sticks were used to provide consistent reflection targets over long test times. Since ultrasound image quality is greatly influenced by the medium through which the sound travels from the transducer to the target and then back, several criteria were established to identify usable ultrasound phantom materials. (1) The material should exhibit low attenuation as measured by a high pixel intensity in the target reflection, meaning that a majority of the acoustic wave energy was able to reach the target and return. (2) The material should exhibit low backscatter as measured by a low pixel intensity in the material between the target and the transducer, meaning that the interfaces between the polymer molecules and air trapped in the material microstructure are not breaking up the coherent acoustic wave and distorting the image. The ratio of target reflection intensity to backscatter intensity was chosen as a relative figure-of-merit to differentiate the performance of the materials. High attenuation and/or high backscatter would reduce image clarity, edge detection, and Doppler velocity accuracy at imaging depths where the vascular cavities are small. The following intensity measurements were taken: front surface reflection as a monitor of delivered acoustic energy, target reflection intensity, and material backscatter intensity. ImageJ software (<http://rsb.info.nih.gov/ij/>) was used to compute the mean intensity of 200 pixels in the areas of interest.

II.E. MRI testing

While NMR relaxometry would be the better choice for characterizing proton rich polymers, the imaging resource available was a Philips Achieva 3T MRI scanner. Each of the materials was tested for use in the proposed flow phantom design using developmental ultrashort echo (UTE) and standard spin echo (SE) pulse sequences. The contrast wells in the samples were filled with water to provide a contrast relative to the sample material. To provide the water mass required for the scanner to calibrate the hydrogen frequency, a dish of water was placed with the samples in a corner of the sample tray. A SE scan was performed to discover the contrasts of the materials relative to water and each other. As the sample materials are not uniformly hydrated with unbound water as are tissues, they were expected to have an extremely short $T2^*$, where $T2^*$ is defined as the time constant describing the exponential decay of signal, due to spin-spin interactions, magnetic field inhomogeneities, and susceptibility effects. The $T2^*$ value of the samples were determined using a dual echo 3D UTE scanning sequence⁹ with the following

parameters: voxel size $0.78 \times 0.78 \times 5 \text{ mm}^3$; TR 45 ms; flip angle (FA) 15° ; 2392 radial trajectories; 30 slices. The achieved minimum echo time (TE) was $90 \mu\text{s}$ and the following echo times were chosen for imaging: $140 \mu\text{s}$; $200\text{--}900 \mu\text{s}$ in $100 \mu\text{s}$ steps; $1000\text{--}10\,000 \mu\text{s}$ in $1000 \mu\text{s}$ steps. The T_2^* of the samples was computed from the pixel signal intensity at each TE using a two-compartment model. According to this model, the MR signal (y) is given by

$$y(\text{TE}) = a_1 e^{-\frac{\text{TE}}{T_{2(1)}^*}} + a_2 e^{-\frac{\text{TE}}{T_{2(2)}^*}} + n, \quad (1)$$

where a_1 and $T_{2(1)}^*$ are the coefficient and T_2^* value of the short T_2^* compartment, respectively, and a_2 and $T_{2(2)}^*$ are the coefficient and T_2^* value of the long T_2^* compartment, respectively. The term n represents a Rician-distributed error term which we neglect because it is 1 order of magnitude smaller than $\max(a_1, a_2)$ for the samples. Using extrapolation for $\text{TE} \rightarrow 0$, we obtain the relation

$$y(0) = a_1 + a_2 = c \quad (2)$$

and determine the value c for each pixel of the samples. The unknowns of the T_2^* two-compartment modeling are then determined by solving the optimization problem

$$\min_{a_1, T_{2(1)}^*, T_{2(2)}^*} \sum_i \left(y(\text{TE}_i) - a_1 e^{-\frac{\text{TE}_i}{T_{2(1)}^*}} + (a_1 - c) e^{-\frac{\text{TE}_i}{T_{2(2)}^*}} \right)^2 \quad (3)$$

such that the unknowns a_1 , $T_{2(1)}^*$, $T_{2(2)}^*$ are larger or equal to zero. The fractions of the spins for the short and long T_2^* components are determined for each pixel by

$$f_1 = \frac{a_1}{c}, \quad (4)$$

$$f_2 = \frac{a_2}{c}. \quad (5)$$

Quantitative shading plots of $(f_1, T_{2(1)}^*)$ of the short T_2^* compartment and $(f_2, T_{2(2)}^*)$ of the long T_2^* compartment were created for the samples.

ImageJ was used to compute the mean intensity of 200 pixels within the materials and the water reference near the center of the samples. The images of acceptable candidate materials for MRI phantoms were expected to show contrast wells with sharp edge detail and visible contrast between the material and the water in the well.

II.F. CT testing

A Philips Gemini 64TF PET-CT scanner calibrated for water was used to test the materials for use in the proposed flow phantom design. The contrast test wells in the samples were filled with water to provide contrast relative to the sample material. The samples were scanned in 1 mm slices at 1 mm steps in nine combinations of exposure/dose (mAs) and tube voltage (kVp), comprising three settings of exposure for each of three tube voltage settings. ImageJ was used to compute the mean Hounsfield Unit (HU) value of 200 pixels within the materials near the center of the sample. The images of acceptable candidate materials for CT phantoms were expected to

show contrast wells with sharp edge detail and visible contrast between the material and the water in the well.

III. RESULTS

III.A. Literature search

Table I contains the phantom materials most commonly referenced in the literature reviewed for this study. The table lists each material's characteristics against the properties desired for the proposed flow phantom design.

Agar is commonly used for sealed ultrasound targets or for short lived training and research models which do not require dimensional stability. It can require additives to prevent biological growth and water immersion and/or refrigeration to prevent decomposition in air. Aquaflex gel pads are commonly used for clinical ultrasound patient examinations but shrink dimensionally when exposed to air. Polyacrylamide (PAA) has toxicity issues and changes dimensionally over time. Polyvinyl alcohol (PVA) is difficult to prepare and requires special storage to prevent decomposition. Oil gel and gelatin are attractive due to their availability and low cost but dissolve in the presence of fluid flow, are not generally self-supporting, and have decomposition issues.

The literature search produced a database of human tissue and industrial casting material properties with 200+ entries and the relevant tissues and materials are listed in Table II sorted by the density property. Manufacturer data sheets reported physical properties such as hardness, density, elongation, and opacity, whereas the ultrasound imaging literature (as a modality example) reported density in addition to acoustic properties such as velocity, impedance, and attenuation. As exhaustive measurement and correlation of all properties for each material for each modality was beyond the scope of the study, the study focused on how each of the selected test materials performed against the desired image quality criteria.

The candidate materials were selected against the desired properties of the proposed flow phantom and included five two-part silicones (P-4, P-125, 10T, 27T, T-4) and one two-part polyurethane (RP-6400). Two-part materials involve mixing a base/resin with a hardener/catalyst to start the curing process. Two of the silicones were cured by condensation with titanium (10T, 27T), two were cured by condensation with platinum (P-125, P-4), and one of the silicones was cured by

TABLE I. Overview of common phantom materials and characteristics.

Substance	Preparation	Toxicity	Dimensional		References
			stability	Bioactive	
Agar	Simple	No	No	Yes	2, 3, 10
Aquaflex pad	N/A	No	No	No	
Polyacrylamide	Complex	Yes	No	No	10, 11
Polyvinyl alcohol	Moderate	Irritant	No	No	2, 12, 13
Silicone	Simple	Low	Yes	No	10
Polyurethane	Simple	Yes	Yes	No	14, 15
Oil gel	Simple	Low	No	No	15
Gelatin	Simple	Low	No	Yes	3, 4

TABLE II. Properties of human abdominal tissues and industrial casting materials. The materials appearing in bold were tested in this study. Please refer to the Appendix for abbreviations used in the table.

Material	Opacity	Cure	SG	Density (kg/m ³)	Mix visc. (kcP)	Mix life (min)	Hardness	Elongation (%)	Veloc. long. (m/s)	Z (Mrayl)	Attn (dB/cm MHz)	Reference
Human fat				924					1450	1.34	0.50	Bushberg (Ref. 16)
Water @ 25C			1.000	998					1497	1.49		Bushberg (Ref. 16)
P-4	Clear	CCP	1.010	1010	7.5	120	41	150				Silicones, Inc.
Oil gel 1				1040					1480		0.40	Kondo (Ref. 15)
RP-6400	Opaque			1040	13	30	52	420	1500	1.56		Zell (Ref. 10)
Agar 2%				1040					1500	1.57	0.40	Zell (Ref. 10)
Human blood				1058					1560	1.65	0.18	Bushberg (Ref. 16)
Oil gel 2				1060					1580		1.80	Kondo (Ref. 15)
Human liver				1061					1555	1.64	0.40	Johnston (Ref. 17)
Human muscle				1068					1600	1.71		Bushberg (Ref. 16)
Mold max 15T		CCT	1.080	1080	20	45	15	600				Smooth-on
Mold max 10T	Transl.	CCT	1.090	1090	14	60	10	586				Smooth-on
P-125	Clear	CCP	1.090	1090	100	60	40	250				Silicones, Inc.
Polyacrylamide 10%				1090					1580	1.73	0.70	Zell (Ref. 10)
Polyvinyl alcohol				1100					1570	1.74	2.90	Zell (Ref. 10)
T-4	Transl.	AC		1100	35	90	40	400				Dow, Inc.
Mold max 27T	Transl.	CCT	1.110	1110	30	45	27	400				Smooth-on
Human skin				1110					1540	1.71	9.20	Duck (Ref. 18)

addition (T-4). Condensation and addition curing refer to “two methods of vulcanizing (molecular crosslinking) liquid silicone which offer differences in controllability of cure rates and cured properties such as shrinkage and abrasion resistance.” The candidate materials possessed hardness (Shore A) values from 10 (10T) to 52 (RP-6400), densities from 1010 kg/m³ (P-4) to 1110 kg/m³ (27T), and mixed viscosities from 7500 cP (P-4) to 100 000 cP (P-125). The costs ranged from \$21/kg (P-4) to \$50/kg (T-4). Manufacturers included: 10T and 27T from Smooth-On, Inc. (Easton, PA); P-4 and P-125 from Silicones, Inc. (High Point, NC); T-4 from Dow, Inc. (Midland, MI); RP-6400 from Freeman Manufacturing and Supply (Avon, OH).

III.B. Test sample fabrication

The samples were cast in a cylindrical shape with a 2.54 cm (1 in.) diameter and a 5 cm (2 in.) height as shown in Fig. 1. Postcure opacity ranged from optically clear (P-4, P-125), to translucent (10T, 27T, T-4), to opaque (RP-6400). RP-6400 exhibited an opaque golden yellow color.

All samples were prepared according to the manufacturers specifications of a 10:1 mix of base and catalyst that typi-

cally yielded a sample volume per unit mass of mixed material of 0.9 l/kg (25 in.³/lb). Silicones P-4, P-125, T-4, 10T, and 27T were prepared in a well ventilated room as recommended and did not emit noticeable noxious fumes during preparation. Polyurethane RP-6400 was prepared and cured under an externally vented hood as recommended. None of the samples exhibited postcure odors or surface residues.

Single diagonal rectangular cavities were molded into the P-4, T-4, 10T, 27T samples. Two opposing diagonal rectangular cavities were molded into the RP-6400 sample. Two vertical round holes of different diameters were drilled in the P-125 and RP-6400 samples.

As the process of thoroughly mixing the base and catalyst introduces microbubbles, all manufacturers recommended a vacuum degas prior to casting. To degas the higher viscosity materials within working times ranging from 30 (RP-6400) to 120 min (P-4), a thin layer of the material was placed in a flat wide shallow tray and the material was exposed to alternating cycles of vacuum and atmospheric pressure. One manufacturer recommended cycling between a vacuum of 711 mm Hg (28 in. Hg) and an air pressure of 5931 mm Hg (203 in. Hg) (100 psi) such that the vacuum cycle would pull bubbles out of the mixture by attracting the trapped gas, and, the air

FIG. 1. Silicone and polyurethane test samples.

pressure would push the bubbles out by forcing the molecules in the mixture together. Depending on the material, a container volume of five times the volume of the mixture was used to allow the degassing bubbles to expand and “break” under vacuum. The low viscosity P-4 material degassed quickly within its stated working time at atmospheric pressure allowing degassing to be performed in the mold itself. When degassed under vacuum, the uncured P-4 was easily drawn through microcracks in the mold walls. The high viscosity samples (P-125, T-4) were difficult to degas as bubbles would not rise through any thickness of the mixture quickly (if at all). Degassing of all materials was slowed by the curing process which increased the viscosity of the mixture over the working time from an initially flowing mixture to a solid (fully cured) material. It was difficult (if not impossible) to prevent reintroduction of bubbles while pouring the degassed mixtures into the mold and success with high viscosity materials required postpour degassing in the mold itself. Pouring a continuous stream in one spot yielded the fewest bubbles.

III.C. Ultrasound results

The ultrasound images of the test samples are shown in Fig. 2. The V6-2 transducer implemented a long axis phased array scan that appeared as a bright arc from left to right at the top of the images.

The P-4 sample exhibited a bright, thin, and uniform front surface reflection layer, low backscatter, and a bright reflection from the wood stick target pressed into the contrast well of the sample. The 10T sample exhibited a bright, thin, and uniform front surface reflecting layer, noticeable backscatter, and a bright reflection from the wood stick target. The 27T sample exhibited a bright, thin, and uniform front surface reflecting layer, less backscatter than the 10T, and a bright reflection from the wood stick target. The 10T sample exhibited more backscatter than the harder and more dense 27T. The T-4 sample exhibited a bright nonuniform front surface reflecting layer, nonuniform backscatter, and a faint reflection from wood target. The P-125 sample exhibited a bright, thin, and uniform front surface reflecting layer, no backscatter, and no reflection from the wood stick target. The RP-6400 sam-

FIG. 2. Ultrasound images showing backscatter and target reflections.

FIG. 3. Ultrasound results: Reflection and backscatter characteristics of the tested samples.

ple exhibited a bright, thick, and very nonuniform reflecting layer deep into the sample, bright widespread backscatter, and no target reflection.

The ultrasound reflection measurements are plotted in Fig. 3 and listed in Table III. The front reflection levels of all materials were within 10% of each other, a variation due to differences in transducer-to-sample distance, and varying material hardness (stiffness) which influences acoustic reflection.

The P-4, 10T, and 27T target reflections were slightly attenuated from the front surface reflection levels, suggesting low attenuation despite differences in material properties and cure chemistry. The T-4 target reflection was noticeably lower suggesting higher attenuation and backscatter. The P-125 target reflection was very low suggesting very high attenuation since the associated backscatter was very low. The RP-6400 target reflection was not measurable and further literature search uncovered a chemical cousin of the RP-6400, RP-6401 (Freeman) that has an attenuation of 100 dB/cm MHz which is too high for acoustic imaging if they share this property.

The P-4 backscatter was the lowest in the group and the RP-6400 was the highest. The T-4 was close to the 10T, and the 27T was in the middle of the range. The large difference in backscatter intensity between the 10T and 27T might be explained by more air intrusion into microstructure of the less dense 10T and/or their difference in hardness. The P-125 backscatter was very low.

TABLE III. Ultrasound results: Data for Fig. 3 with a computed figure-of-merit.

Material	Front reflection	Internal backscatter	Target reflection	Figure-of-merit (dB)
P-4	229.9	3.5	219.3	80.0
P-125	226.9	15.8	0.0	N/A
27T	230.5	50.5	217.8	6.3
T-4	238.6	103.2	161.4	1.9
10T	249.5	108.0	221.6	3.1
RP-6400	246.3	123.9	0.0	N/A

FIG. 4. MRI results: Images of spin echo and ultrashort echo scans at various values of pulse repetition time (TR) (ms), TE (ms), and flip angle (degrees). The TE 0 in the figure is 140 μ s rounded to 0 ms.

The last column of Table III lists the ratios of target reflection to backscatter for the materials in decibels (dB) as a figure-of-merit where higher values indicate more reflected signal and less backscatter. The P-4 exhibited the best performance against this metric.

III.D. MRI results

Figure 4 shows coronal SE and UTE images of the samples in the tray with the water reference dish in the upper left corner. Table IV lists the relative intensities between the materials and the water reference.

The left-most image in Fig. 4 shows a T1-weighted spin echo scan with a TE of 10 ms, TR of 600 ms, and flip angle of 70°. The 10T and 27T samples are nearly the same intensity as the water reference dish in the upper left hand of the image, and, the 10T appears slightly lighter in intensity than the 27T as confirmed by the ratios provided in Table IV. The edge definition of the 10T and 27T contrast wells was distinct. The intensities of the P-4 and P-125 materials are indistinguishable from the background air intensity (black). The intensity of the RP-6400 material was indistinguishable from the background air intensity (black) and the water in the contrast wells was visible with good edge definition. The middle image of Fig. 4 shows a UTE scan with a TE of 140 μ s, TR of 45 ms, and flip angle of 15°. The 10T and 27T samples are nearly identical in intensity to the water reference as confirmed in Table IV. The contrast wells of both samples are distinguishable from the material with good edge definition. The intensities of the P-4, P-125, and RP-6400 materials are

nearly equal in intensity and slightly darker than the water reference. The RP-6400 contrast wells are distinguishable from the material with good edge definition. The right-most image of Fig. 4 shows a UTE scan with a TE of 1 ms, TR of 45 ms, and flip angle of 15°. The 10T and 27T samples are slightly darker than the water reference and have similar intensities as confirmed by the data in Table IV and the contrast wells have good edge definition. The intensities of the P-4 and P-125 are identical and their contrast wells are not visible. The RP-6400 was indistinguishable from air (black) and the contrast wells are not visible.

Figure 5 shows shading plots for the T2* measurements and Table V lists the associated values for each material. The T2* quantities were obtained by interpolation or extrapolation based on the data for the two-compartment model. The UTE technique clearly differentiates silicones and polyurethane chemistries and shows a slight difference in the long T2* value between the titanium cured 10T/27T and the platinum (P-4, P-125) and addition cured silicones (T-4).

III.E. CT results

Figure 6 provides cross-sectional views of the sample CT scans detailing the contrast wells containing water. The P-4 sample shows an air bubble halfway up the diagonal well, the P-125 shows an air bubble near the top of the water well, and the RP-6400 shows air above both water columns.

The Hounsfield values of each material are listed in Table VI and plotted in Fig. 7. The error bars in Fig. 7 represent the scanner measurement uncertainty as a percentage of the measured value. All of the silicone materials (P-4, P-125, T-4, 10T, 27T) exhibited measurable and visible contrast between the water (0 HU) in the contrast wells and the

TABLE IV. MRI results: Material intensities for SE and UTE scan sequences relative to water. The entries of less than 100 dB are a result of RP-6400 intensity values close to zero.

Material	SE (dB)	UTE TE 140 μ s (dB)	UTE TE 1 ms (dB)
RP-6400	< -100	-1.3	< -100
P-125	-22.0	-1.8	-6.3
P-4	-15.4	-2.9	-6.3
10T	0.7	-0.4	-1.6
27T	-0.7	-0.4	-1.8

FIG. 5. MRI results: Shading plots of T2* material intensities.

TABLE V. MRI results: T2* mean material intensities.

Material	Short T2* (μ s)	Long T2* (μ s)	Short T2* (%)	Long T2* (%)
P-4	25	2250	5	95
P-125	25	2250	5	95
T-4	35	2250	5	95
27T	25	3300	5	95
10T	25	3300	5	95
RP-6400	535	250	95	5

material. Although the P-4 exhibited the lowest contrast of the silicones, it exhibited the sharpest edge detail.

The Hounsfield values of the samples did not vary across 100/200/250 mAs exposure settings at constant tube voltages (kVp). The Hounsfield values of the samples did decrease nonlinearly with increasing tube voltage as shown in Fig. 7 at constant exposure levels. The silicones 10T and 27T tracked each other with an offset that was also visible in their relative brightness in Fig. 6 and the measured values in Table VI. Silicones T-4 and P-125 tracked each other very closely across the tube voltage settings despite very different cure chemistries. The polyurethane RP-6400 exhibited a nearly zero contrast to water and very low variation across all tube voltages as seen in Figs. 6–8 and Table VI. The physical features of the RP-6400 sample are detailed in Fig. 8 to show that the water column above the silicon bottom plugs (white) and below the meniscus was nearly indistinguishable from the sample material itself.

IV. DISCUSSION

IV.A. Desired properties

All of the materials were readily available in 2 kg (~5 lb) quantities and were delivered within a week after ordering from the manufacturers or their local representatives. The molding cost of the proposed phantom using the P-4 silicone would be approximately \$21, which was considered a reasonable project expense for a durable and reusable phantom.

None of the materials were listed as extreme fire hazards by the manufacturers. The fumes from liquid RP-6400 polyurethane were listed as an inhaled toxic hazard and are mitigated by use of an externally vented hood.

The inner and outer dimensions of the samples did not change perceptibly during testing or handling. As an indirect measure of dimensional stability under flow pressure, the wood targets for ultrasound testing were slightly larger than

TABLE VI. CT results: Hounsfield values at 200 mAs.

Material (HU)	80 kVp	120 kVp	140 kVp
27T	401.0	243.8	205.5
10T	371.1	219.4	182.4
P-125	364.9	211.3	175.3
T-4	352.9	212.5	171.7
P-4	264.3	133.0	101.7
RP-6400	8.1	6.8	5.3

FIG. 7. CT results: Material intensity variation with kVp at 200 mAs.

FIG. 8. CT results: Image of RP-6400 at 120 kVp/200 mAs showing nearly zero contrast to water.

FIG. 6. CT results: Cross-sections showing water in contrast wells at 120 kVp/200 mAs.

the contrast wells and this applied an internal stretching force on the inner diameter of the wells. The wood targets were installed and removed many times without material loss, cracking, or change in fit or insertion/removal force. The RP-6400 was found to reproduce surface details as fine as 0.18 mm (0.007 in.).

All of the materials were soiled during machining and general handling and all were easily cleaned. The samples did not dissolve, change color/opacity/appearance after exposure to water, or sitting in air for the several months of testing, nor did they host molds or develop odors after repeated water exposure.

The optically clear samples greatly facilitated the degassing process development and the location of bubbles in water injected into the contrast wells.

IV.B. Other applications

From handling the materials during testing, it became evident that the differences in hardness/density properties between these materials and their ability to “self-heal” small penetrations might also be exploited to create reusable needle placement training phantoms where the student would be able to feel the changes in penetration force at the boundaries between the materials. For example, the tactile feeling of a needle penetrating skin/muscle/bone transition might be reasonably simulated using 10T for skin, 27T or P-4 for muscle, and P-125 or RP-6400 for bone. Phantoms containing vascular structure could give anatomically accurate positional feedback for blood drawing or spinal tap procedure training with fluid and/or flow in the cavities of interest. The relative material contrasts documented might also be used to create phantoms for imaging based radiological and interventional procedure training.

V. CONCLUSIONS

Based on study data and the stated selection criteria, the P-4 silicone provided sufficient material contrast to water and edge detail for use across all imaging modalities with the benefits of availability, low cost, dimensionally stable, non-toxic, nonflammable, durable, cleanable, and optical clarity. The RP-6400 polyurethane provided excellent edge detail in MRI testing and should be considered for use as a water reference in CT phantoms. The 10T and 27T silicones should be considered for use as a water reference in MRI phantoms.

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APPENDIX: NOMENCLATURE

AC = addition cure
 Attn = acoustic attenuation
 CCP = condensing cure with platinum
 CCT = condensing cure with titanium
 CT = computed tomography imaging
 Cure = cure chemistry
 Elongation = dimensional stretch before tearing
 Hardness (Shore A) = A measure of a material's stiffness (resistance to compression) as defined by ASME standards
 kCp = thousands of centipoise (cP)
 Mix life = working time before material cures (hardens)
 Mix visc. = viscosity at time of mixing
 MRI = magnetic resonance imaging
 SG = specific gravity
 Transl. = translucent
 Veloc. long. = acoustic wave velocity in the longitudinal direction
 Z = acoustic impedance

^{a)}Electronic mail: bryan.yunker@ucdenver.edu

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