The design and fabrication of two portal vein flow phantoms by different methods

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Purpose: This study outlines the design and fabrication techniques for two portal vein flow phantoms.

Methods: A materials study was performed as a precursor to this phantom fabrication effort and the desired material properties are restated for continuity. A three-dimensional portal vein pattern was created from the Visual Human database. The portal vein pattern was used to fabricate two flow phantoms by different methods with identical interior surface geometry using computer aided design software tools and rapid prototyping techniques. One portal flow phantom was fabricated within a solid block of clear silicone for use on a table with Ultrasound or within medical imaging systems such as MRI, CT, PET, or SPECT. The other portal flow phantom was fabricated as a thin walled tubular latex structure for use in water tanks with Ultrasound imaging. Both phantoms were evaluated for usability and durability.

Results: Both phantoms were fabricated successfully and passed durability criteria for flow testing in the next project phase.

Conclusions: The fabrication methods and materials employed for the study yielded durable portal vein phantoms. © 2014 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4861819>]

Key words: Phantom, flow, portal, hepatic, imaging

1. INTRODUCTION

This study outlines the design and fabrication of durable portal vein flow phantoms based on a study of industrial casting

materials¹ performed in a previous phase of the project where small samples of the materials were imaged with Ultrasound and in magnetic resonance imaging (MRI) and computed tomography (CT) systems.

Flow phantoms offer a range of utility, durability, and repeatability that cannot be obtained from *in vitro* organ or animal use. The study of blood flow through the human liver is key to the study of disease and the improvement of related surgical techniques as discussed in the next three examples. (1) Malignant hepatic tumors can be eradicated by heating the tumor to the necrosis (cell death) temperature of 55 °C (131 °F) using a radiofrequency (RF) probe, however, the success of the procedure is limited by localized blood flow that removes delivered heat^{2,3} and may prevent some or all of the tumor from reaching the point of necrosis. (2) Hepatocytes (liver cells) exposed to chemical toxins such as alcohol or diseases such as Hepatitis can die and form a fibrous scarring (fibrosis) of the liver lobules which can increase the resistance to blood flow through the liver and result in portal hypertension.^{4,5} (3) The study of hepatic metabolism⁶ can also involve the study of blood flow. In all of these examples, the use of flow phantoms created from human⁷ or animal imagery should provide more accurate modeling than phantoms fabricated from manufactured tubing or geometrical approximations of vessels.^{8–12}

One phantom was fabricated within a solid block of silicone with fluid flow contained within the phantom body for imaging with Ultrasound on a table or within medical imaging scanners such as MRI, CT, PET (positron emission tomography), and SPECT (single photon emission computed tomography) that might be damaged by uncontained liquids. As an alternative use of the construction methods developed for the solid block phantom, another phantom was constructed as a thin walled tubing structure using liquid latex for use with Ultrasound imaging in water tanks.

2. METHODS AND RESULTS

2.A. Portal mesh

A three-dimensional surface mesh of the portal vein was obtained from the Visual Human Male™ (ToLTech, Inc., Aurora, CO) for use in the flow phantom fabrication as shown in the left-hand frame of Fig. 1.

This mesh source was chosen as the software tools required to segment and extract the mesh from patient-specific imagery were not available. The portal mesh (a dataset of triangular “faces” and associated corner “vertices”) was delivered in the standard OBJ and STL digital file formats used by computer aided design (CAD) software.

FIG. 1. Portal mesh in original and edited forms.

FIG. 2. Solid geometry casting pattern design used for the phantom fabrications.

The mesh was edited with the *MeshLab* (<http://www.meshlab.sourceforge.net>) software package at the vertex/face level to remove branches that could not be practically attached to outlet ports, to close the resulting holes in the mesh, and to remove vessel fragments and unattached vertices that interfere with surface smoothing and printing.

The “surface relaxation” function of the *GeoMagic* (Morrisville, NC) software package was used to smooth the mesh and yielded the optimal surface representation of the several smoothing functions offered. The smoothed portal vein mesh is shown in the right-hand frame of Fig. 1. Another *GeoMagic* function was used to reduce the number of faces and vertices used to represent the mesh to accommodate the *SolidWorks* 2010 (Waltham, MA) CAD software package import limit of 20 000 faces for STL based solid models.

2.B. Pattern design

The cleaned and smoothed mesh was imported to the *SolidWorks* 2010 3D CAD software package for the addition of inlet and outlet pipes at the end of each vascular branch to create a casting “pattern” for the flow phantom molding process as shown in Fig. 2. The geometrical tube at the top of the figure is the portal vein inlet and the geometrical tubes at the bottom of the figure are the portal branch outlets. The black shaded structure between the geometrical tubes is the portal vein mesh converted into a solid body.

The inner diameters of the inlet and outlet ports were sized to accommodate standard plastic barbed tubing adapters [6.4 mm (1/4 in.), 9.5 (3/8 in.), 12.7 mm (1/2 in.)] in keeping with the elongation limits of the silicone and latex materials to prevent cracking and ripping during barb insertion and removal. To prevent the outlets from restricting the flow from the vessel ends, each vessel was connected to an outlet structure much larger than the vessel diameter.

2.C. Pattern printing

The pattern design file was processed with Stratasys (Eden Prairie, MN) *Insight* and *Control Center* software to create the files required for “printing” the pattern as a 3D plastic

structure on a Stratasys Fortus 200mc hot plastic deposition rapid prototyping printer. As the printer prints plastic at a physical resolution of 0.18 mm (0.007 in.), the previous *MeshLab* and *GeoMagic* editing and smoothing of the mesh were critical steps since the printer resolution was sufficient to reproduce any geometry errors in the surface.

Two printing materials were chosen as inputs to the printing process. “WaterWorks,” a brown colored brittle material that dissolves when immersed in a base pH water solution at 65 °C (150 °F), was chosen for the pattern portal vein structure. Acrylonitrile-butadiene-styrene (ABS), a red colored durable/rigid thermoset plastic, was chosen for supporting the horizontal structures printed with WaterWorks since the plastics cannot be printed into thin air. (Note that for this *pattern making* application, the roles of these materials are reversed from the traditional printing of mechanical parts where the part is printed with the durable ABS material and the brittle dissolvable Waterworks material is used for support. For mechanical parts, the Water Works support material is dissolved post printing, leaving the desired ABS mechanical part).

The 3D printing process starts with a layer of melted plastic deposited onto a model base that snaps into the printer tray. The plastic enters the print head from a spool of small diameter hard plastic and is then heated to the melting point for printing and then cools to a hard plastic shortly after exiting the print head. The printing path of the initial layers form the base of the pattern structure as illustrated in the left-hand frame of Fig. 3. After printing each layer of melted plastic, the tray supporting the model base is lowered to allow the next layer of hot plastic to be printed on top of the previous layer. The build up and printing path of the portal pattern design and underlying support material is shown in the right-hand frame of Fig. 3. The Stratasys *Insight* software allows user selection of materials layer by layer, which is convenient for creating a breakoff layer low in the base to facilitate removal of the pattern from the base after printing. The breakoff was implemented by depositing a layer of the brittle Waterworks material between layers of the rigid ABS support material. More importantly, *Insight* allows control over the printing geometry (pitch and overlap of the deposited beads of hot plastic) which is critical to the creation of pattern features that are robust enough to endure the casting and pattern dissolving

FIG. 3. Printing paths for the pattern base (Left) and phantom and support material structure (Right).

FIG. 4. (Left) Dissolvable Water Works pattern material printed above the ABS support material. (Right) Finished dissolvable portal vein pattern after ABS support material removed by grinding tool.

process without excessive printing time and materials use (a trial and error art form).

The conical caps on the geometrical inlet and outlet tubes comprise a *unique invention* of a self-supporting roof structure which eliminates the need for ABS support material inside of the tubes which would be neither removable nor dissolvable. The WaterWorks pattern material could have been used as an internal roof support structure at the expense of doubling the printing time which was 12 h as implemented. The angle (slope) of the conical caps was determined by the minimum overlap of the beads of plastic deposited on top of each other without falling off the bead below, which sets the maximum horizontal bead pitch. Tubes terminated in domes or flat tops, for example, cannot be implemented without internal support material because the minimum overlap is always exceeded where the structure slope is predominantly horizontal.

The fabricated portal vein pattern is shown in Fig. 4 with and without the ABS support material where the WaterWorks pattern material color is brown and the ABS color is red. The smallest practical vessel diameter with this fabrication process was 1 mm (0.04 in.) due to the delicate process of physically separating the brittle WaterWorks pattern material from the rigid ABS support material without damage to the portal vein pattern features.

Removing the ABS support material from under the WaterWorks pattern material turned out to be difficult and time consuming as the ABS is difficult to cut and melts into grinding tools (properties which make ABS very suitable for the printing of durable mechanical parts). In subsequent pattern fabrications, the support material was changed from ABS to the brittle WaterWorks material and the support structure printing pattern was redesigned with a very thin wall and very low density inner webbing. This support structure design was easily broken away from the more robustly printed WaterWorks pattern.

2.D. Solid body phantom design

A two part silicone, P-4 from Silicones, Inc. (High Point, NC), was selected from the study of industrial casting materials¹ performed in advance of this project phase. P-4

FIG. 5. “Solid Body” silicone phantom casting process steps.

exhibited many of the properties desired for the phantom design including: visible contrast and edge detail between the material and water, readily available, low cost, dimensionally stable, nontoxic, nonflammable, durable, cleanable, and optically clear. Additionally, physical and dimensional stability was desired over physiological and imaging suite temperatures (18/26 °C) (65/80 °F) and at physiological fluid pressure (120 mmHg) (2.3 psi) to maintain the accurate shape of the vascular cavities and 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 agent residues. A chemically and biologically inert material was desired so that the phantom will not degrade or decompose over time when exposed to sunlight, temperature, or inert 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 the cast anatomy for training purposes. A low viscosity material was desired to facilitate the removal of bubbles introduced into the material during mixing and pouring. Manufacturer's specifications along with handling observations during material and phantom evaluation were used to screen and evaluate the properties not explicitly tested in the materials selection and fabrication study phases.

The dimensions of the solid body flow phantom were set to 10 × 10 × 10 cm (1000 cc) (1 L) (61 in³) to accommodate 3D imaging of the full portal mesh. The cost of the solid body phantom was estimated at \$23 from the target phantom volume, the material cost of \$21/kg (\$9.50/lb), and a yielded material volume per unit mass of mixed material of 0.9 L/kg (25 in³/lb), which was considered a reasonable project expense for a durable and reusable phantom.

The solid body phantom was molded in a hexagonal shape to provide flat surfaces for acoustic coupling with Ultrasound and to provide a stable surface when the phantom rests on a lab table or on imaging system patient beds.

2.E. Solid body phantom fabrication

The solid body phantom was fabricated by placing a printed portal vascular pattern into a printed mold and pouring the silicone over the pattern. The casting process followed techniques developed in the materials study¹ to minimize entrapment of bubbles within the phantom that would create

undesirable imaging artifacts. The process steps of the phantom casting process are shown in Fig. 5. The left-hand photo shows the pattern installed in the hexagonal phantom mold which was also printed using the WaterWorks pattern material. The middle photo shows the dissolvable pattern cast within the silicone block prior to the process of dissolving the pattern in a 65 °C (150 °F) jet bath of base pH water. The right-most photo shows the fully demolded solid body phantom and the internal void in the shape of the portal vein branching vasculature.

After 12 h in the dissolving solution, the pattern was not dissolving at an acceptable rate. The rate was increased by connecting the portal inlet of the phantom to the solution pump outlet which forced dissolving solution through the phantom under pressure. Even with this modification, the solution preferred to flow through the larger and more open vessels than through smaller vessels. The flow through the pattern was inhibited by the low porosity of the pattern design, an issue corrected in the thin walled phantom design and fabrication.

A slight “fog” can be seen in the silicone casting of the solid body phantom in the right-hand frame of Fig. 5 that is caused by dissolving solution forced into the polymer microstructure under pressure during the pattern dissolving process. The fog disappeared after several hours in open air. A slight optical blurring can be seen on the hexagonal sides of the phantom in Figs. 5 (middle) and 6 which is an optical effect caused by the slight surface roughness of the mold at the 0.18 mm (0.007 in) printer step resolution. This surface smoothness effect would be diminished with use of a printer with higher resolution.

FIG. 6. “Solid Body” phantom plumbed for leak testing.

FIG. 7. Ultrasound test apparatus for commercial dimensional tubing.

2.F. Solid body phantom evaluation

The solid body phantom is shown in Fig. 6 on a lab bench with barbed inlet and outlet fittings plumbed to a gravity fed water source for leak and durability testing.

The barbed fittings were easily installed and there were no leaks around the inlet/outlet seals or from the phantom body itself over long periods containing standing fluid. The silicon microstructure did not visibly absorb water under gravity driven leak test pressures and flows. The silicon microstructure did not trap a cornstarch contrast dissolved in the test water flow. A water/glycerol mix was not used to simulate blood over concern that the more viscous glycerol would not come out of the phantom cavities and would create a permanent echogenic cloud around the fluid channels that would degrade future Ultrasound images and Doppler measurements. Blood was not used for leak testing for concern that it would penetrate the microstructure and decompose, preventing the phantom from being cleaned to a sterile state. Further smoothing and sealing of the vessels with a lacquer coating of the interior of the portal vascular voids was not implemented for concern the coating would create an impedance mismatch or reflecting surface for Ultrasound at the vessel walls. The optical clarity of the P-4 silicon greatly facilitated air bubble removal from the leak test flow streams. The elongation characteristic of the P-4 silicone was sufficiently high to allow good seals around the barbed tubing fittings without leaking and prevented cracking of the phantom block if attention was paid to the fitting insertion force and the use of a small amount of silicone grease. In future versions, half of each barb fitting will be cast into the phantom itself to provide full mechanical strength for tubing support.

2.G. Thin walled phantom construction

As a precursor to the thin walled phantom construction, an Ultrasound evaluation of commercially available thin walled (0.4–0.8 mm) (1/64–1/32 in.) latex, white silicone, and Tygon™ tubing samples was performed to guide the material selection. The latex samples exhibited the lowest front surface reflection and best lumen definition. The setup for testing commercial dimensional tubing is shown in Fig. 7 with latex test specimens installed.

A liquid latex (Liquid Latex Mold Making Rubber, Aero-Marine, Inc., San Diego, CA) was selected for molding the irregular shape of the portal structure. The thin walled phantom was fabricated by dipping the printed hepatic vascular pattern into the liquid latex. The fabricated thin walled phantom is shown in the left-hand frame of Fig. 8 and was double dipped to ensure coverage yet maintain an average wall thickness of under 1 mm (0.04 in.).

The latex had a low surface tension, a high viscosity, and a long drying time that required rotation of the dipped pattern slowly in three dimensions while the liquid latex dried. The rotation process caused some surfaces on the complex pattern to retain more material than others resulting in minor thickness differences. The fabrication included the formation of a flat round base of latex which maintained the alignment of the otherwise flexible and floppy outlet legs and facilitated barb insertion and seal integrity. The pattern dissolving process was accelerated by redesigning the printing paths of the pattern to create a hollow core throughout the phantom pattern structure. This feature allowed the entire phantom to dissolve from the inside out instead of from end to end as with the solid body phantom. In future, a further reduction in the dissolving time will be achieved by creating a distribution manifold for the solution pump so that solution can be forced through each outlet separately to ensure pressure and flow through each vessel using the portal vein inlet as the drain.

The middle frame of Fig. 8 shows the barbed hose fittings holding the phantom securely to the other side of a thick polyethylene sheet that was used to mount the phantom in the Ultrasound water tank and provide a barrier to water circulation in the tank as shown in the right-hand frame of Fig. 8.

2.H. Thin walled phantom evaluation

The thin walled phantom was plumbed to a gravity fed water source for leak and durability testing under static and

FIG. 8. “Thin Walled” phantom and installation in water tank.

dynamic flow conditions well above normal physiology. The barbed fittings sealed with no leaks and there were no ruptures in the phantom walls. When immersed in the water tank the phantom stayed rigid between the static water pressure outside the phantom and the static and dynamic pressure of the fluid flow within the phantom. The latex material in the thickness fabricated was very resistant to tearing and cutting suggesting that phantoms with even thinner walls would be usable with improvements in dipping/solid bodying technique. The color of the latex darkened over time with exposure to air and water but the material showed no signs of physical degradation over several months. On the path to improved thickness uniformity, the authors have performed preliminary tests with a “spray-on” latex which may enable phantoms of “membrane” thickness.

3. CONCLUSIONS

Solid body silicone and thin walled latex flow phantoms can be successfully fabricated using the commercially available CAD software tools and rapid prototyping methods presented.

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- ¹B. E. Yunker, D. Cordes, A. L. Scherzinger, G. D. Dodd, R. Shandas, Y. Feng, and K. S. Hunter, “An investigation of industrial molding compounds for use in 3D ultrasound, MRI, and CT imaging phantoms,” *Med. Phys.* **40**, 052905 (9pp.) (2013).
- ²R. S. Montgomery, A. Rahal, and G. D. Dodd, “Radiofrequency ablation of hepatic tumors: variability of lesion size using a single ablation device,” *AJR Am. J. Roentgenol.* **182**, 657–661 (2004).
- ³S. N. Goldberg, P. F. Hahn, E. F. Halpern, R. M. Fogle, and G. S. Gazelle, “Radio-frequency tissue ablation: effect of pharmacologic modulation of blood flow on coagulation diameter,” *Radiology* **209**, 761–767 (1998).
- ⁴D. C. Rockey, “Hepatic blood flow regulation by stellate cells in normal and injured liver,” *Semin. Liver Dis.* **21**, 337–349 (2001).
- ⁵S. K. Sarin, K. K. Sethi, and R. Nanda, “Measurement and correlation of wedged hepatic, intrahepatic, intrasplenic and intravariceal pressures in patients with cirrhosis of liver and non-cirrhotic portal fibrosis,” *Gut*, **28**, 260–266 (1987).
- ⁶B. Barbaro, G. Palazzoni, R. Prudenzeno, A. Cina, R. Manfredi, and P. Marano, “Doppler sonographic assessment of functional response of the right and left portal venous branches to a meal,” *J. Clin. Ultrasound* **27**, 75–80 (1999).
- ⁷C. A. Taylor and C. A. Figueroa, “Patient-specific modeling of cardiovascular mechanics,” *Annu. Rev. Biomed. Eng.* **11**, 109–134 (2009).
- ⁸N. J. Raine-Fenning, N. M. Nordin, K. V. Ramnarine, B. K. Campbell, J. S. Clewes, A. Perkins, and I. R. Johnson, “Determining the relationship between three-dimensional power Doppler data and true blood flow characteristics: an *in vitro* flow phantom experiment,” *Ultrasound Obs. Gynecol.* **32**, 540–550 (2008).
- ⁹J. Brunette, R. Mongrain, G. Cloutier, M. Bertrand, O. F. Bertrand, and J. C. Tardif, “A novel realistic three-layer phantom for intravascular ultrasound imaging,” *Int. J. Cardiovasc. Imaging* **17**, 371–381 (2001).
- ¹⁰R. O. Bude and R. S. Adler, “An easily made, low-cost, tissue-like ultrasound phantom material,” *J. Clin. Ultrasound* **23**, 271–273 (1995).
- ¹¹S. Inglis, K. V. Ramnarine, J. N. Plevris, and W. N. McDicken, “An anthropomorphic tissue-mimicking phantom of the oesophagus for endoscopic ultrasound,” *Ultrasound Med. Biol.* **32**, 249–259 (2006).
- ¹²C. A. Taylor, T. J. Hughes, and C. K. Zarins, “Finite element modeling of three-dimensional pulsatile flow in the abdominal aorta: relevance to atherosclerosis,” *Ann. Biomed. Eng.* **26**, 975–987 (1998).