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Development of patient-specific molecular imaging phantoms using a 3D printer

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Purpose: The aim of the study was to investigate rapid prototyping technology for the production of patient-specific, cost-effective liquid fillable phantoms directly from patient CT data.

Methods: Liver, spleen, and kidney volumes were segmented from patient CT data. Each organ was converted to a shell and filling holes and leg supports were added using computer aided design software and prepared for printing. Additional fixtures were added to the liver to allow lesion inserts to be fixed within the structure. Phantoms were printed from an ultraviolet curable photopolymer using polyjet technology on an Objet EDEN 500V 3D printer.

Results: The final print material is a clear solid acrylic plastic which is watertight, rigid, and sufficiently durable to withstand multiple assembly and scanning protocols. Initial scans of the phantoms have been performed with Tc-99m SPECT and F-18 PET/CT.

Conclusions: The organ geometry showed good correspondence with anatomical references. The methodology developed can be generally applied to other anatomical or geometrical phantoms for molecular imaging. © 2014 American Association of Physicists in Medicine. [http://dx.doi.org/10.1118/1.4887854]

Key words: Rapid prototyping, additive manufacturing, anthropomorphic phantom, quantitative imaging, CAD

1. INTRODUCTION

Anatomical phantoms are widely used in molecular imaging for both qualitative and quantitative assessment of image quality.1,2 These phantoms are often expensive and seldom specific to the patient or cohort of interest. We have previously demonstrated the benefit of a patient specific phantom for analysis of a patient undergoing I-131 mIBG dosimetry.3, 4 In that study the geometry of the tumor was shown to significantly affect the accuracy of quantification, and that patient specific optimization of the imaging and dosimetry protocols were necessary.

Presently a phantom is required for quantitative imaging analysis of Y-90 DOTATATE radiopeptide therapies for neuroendocrine tumors. These patients often present with multifocal hepatic lesions and quantification of Y-90 uptake is difficult,5 at present no commercially available phantoms are able to adequately represent the distribution of activity observed in this cohort. The aim of this study was to investigate the feasibility of rapid prototyping technology to produce individualized, cost effective, liquid fillable phantoms directly from patient CT data. Rapid prototyping has been available for almost 30 years6 primarily for the manufacture of scale models and product prototypes. Also known as solid freeform fabrication, additive manufacturing, and more recently 3D printing, advances have shown widespread appeal with desktop and home systems now available. A phantom was developed with patient-realistic abdominal organs including, liver, spleen, kidneys, and multipositional lesions using anatomical information obtained directly from patient CT data and printed using an Objet Eden 500V 3D printer. The methodology developed can be generally applied to other anatomical or geometrical phantoms.

2. MATERIALS AND METHODS

Anatomical data were obtained from the CT component of a half-body PET/CT scan (140 kVp, 50 mAs, 1.17 mm isotropic contiguous voxels) without IV contrast. Organs were delineated and segmented to create a new dataset containing only the outlined volumes. Figures 1(a) and 1(b) show the original CT slice and segmented organ outlines. Organ volumes were exported to the Delft Visualization and Image processing Development Environment (DeVide) (Ref.7) for smoothing and surface rendering. Organs were segmented and a 3D isosurface generated for each organ of interest represented by a series of triangles [Fig. 1(c)]. To remove the CT pixelation, the 3D surface mesh was smoothed using a windowed sinc function interpolation kernel [Fig. 1(d)]. To reduce the size of the final file a quadric decimation filter was applied to decrease the number of triangles in the triangulation mesh defining the isosurface. The mesh was then saved as a binary stereolithography (STL) file. The STL files were imported into the Autodesk® meshmixer software (Autodesk Inc) for further manipulation before printing. Imperfections in the mesh were smoothed out manually and each organ converted to a shell, with wall thickness of 2 mm. Surfaces were extruded outward so that the inner volume of the shell remained the same as the imported volume. During manipulation the organ volume was monitored to ensure it did not significantly differ from the original patient dataset. To facilitate
printing each organ was constructed in two halves. Smaller organs were glued together after manufacture. To represent our patient cohort the phantom was required to have different multifocal activity distributions within the liver. The phantom was therefore designed to allow multiple fillable inserts to be placed within the organ. A 10 mm flange with screw fittings was added around the periphery of each half, allowing them to be screwed together. Further screw fittings for lesion phantoms were placed at various positions around the surface of the liver. These screw holes allowed the phantoms to be placed inside or outside the liver as required. Similar fittings were also added on all organs for leg supports. Figure 1(e) shows the finished liver design with flange and screw fittings. Figure 1(f) depicts one possible configuration with fillable inserts placed inside the liver section. When not in use, screw fittings can be sealed with standard M6 nylon screws.

Spherical tumor inserts were designed for insertion into the finished phantom using the meshmixer software. Spheres with diameters of 5, 10, 20, 30, 40, and 50 mm were designed with standard M6 screw fixing. Sphere wall thicknesses were 2 mm for the larger spheres decreasing to 0.3 mm for the smallest sphere. Spheres were designed to be connected to the liver with detachable support rods. Holes of 1 mm through these rods allow the spheres to be emptied or filled with a 4-in. (102 mm) 19 gauge needle without the need to reopen the liver phantom. Phantoms were printed using an Objet EDEN 500V (Stratasys Ltd. © 2013). The printer uses a combination of stereolithography and inkjet technology. A 16 μm layer of liquid ultraviolet curable photopolymer is printed onto the build tray. An ultraviolet laser then cures the resin solidifying the pattern traced on the tray. This process is then repeated for each layer. Where overhangs or domed shapes are required a removable support material is printed on the under layers to prevent the structure collapsing before curing (Fig. 2).

Various photopolymer resins are available for printing; in this case a translucent resin was chosen (Objet VeroClear FullCure810).

3. RESULTS

A photograph of the liver section with the support material removed is shown in Fig. 3(a). The completed organs in the correct anatomical arrangement are shown in Fig. 3(b).

Elemental composition of the print material is primarily a mixture of acrylic monomers and oligomers, with a small proportion (<2.5%) of a photoinitiator. Using the chemical composition of the uncured photopolymer the effective atomic number of the build material was estimated to be between 6.47 and 7.37 depending on the photoinitiator. Material density was measured at 1.16–1.20 g/cm³. Measured Hounsfield units were 134 ± 15 compared to 126 ± 15 for polymethylmethacrylate. Figure 4 shows transaxial and coronal CT slices through the phantom. Dimensions for each organ are summarized in Table I with comparisons to the original patient, measured from CT.

Figure 5 shows transverse slices through the phantom measured with F-18 PET [Fig. 5(a)] and Tc-99m SPECT [Fig. 5(b)]. Hot and cold lesions have also been placed within the liver.

4. DISCUSSION

A multicompartmental anthropomorphic test phantom was constructed based on real patient anatomy. The phantom was designed using standard nuclear medicine processing software and software freely available from the internet. As the phantom is designed using CAD further copies can be easily made with modifications to the design as necessary to
suit specific requirements. The final structure was watertight, rigid, and sufficiently durable to withstand multiple assembly and scanning protocols. The design of the phantom fulfilled the requirements that the anatomical detail replicated the patient geometry and offered more flexibility for insert placement than commercially available designs, yet allowed reproducible construction on reassembly. In future work this phantom will be used to assess the quantitative accuracy of In-111/Y-90 DOTATATE dosimetry protocols to explore the effect of the different activity distributions observed clinically. Although the current design is limited to piecewise activity concentrations future work will also concentrate on development of the phantom to introduce porous and expandable inserts for producing nonhomogenous and dynamic activity distributions.

Further advances in this technology promise to offer more flexibility in design at a reduced cost compared to traditional phantoms and could become a more routine method of phantom manufacture.

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**TABLE I. Phantom dimension measurements compared to patient organ dimensions.**

|                  | Patient (mm) | Phantom (mm) | Difference (%) |
|------------------|--------------|--------------|----------------|
| Liver craniocaudal | 182          | 180          | 1              |
| Liver anterior/posterior | 180          | 180          | 0              |
| Spleen maximum extent | 102          | 104          | −2             |
| Right kidney long axis | 102          | 98           | 4              |
| Right kidney short axis | 51           | 52           | −2             |
| Left kidney long axis | 96           | 91           | 5              |
| Left kidney short axis | 46           | 43           | 7              |

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**FIG. 5.** F-18 PET (a) and Tc-99m SPECT scan of phantom. Each compartment is filled with a different concentration of isotope with “hot” and “cold” lesions within the liver.

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