# Abdo-Man: A 3D Printed Anthropomorphic

# Phantom for Validating Quantitative SIRT

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**Keywords**

SIRT, 3D printing, phantoms, quantification, dosimetry, microspheres

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1       **Abstract**

2    **Background:** The use of selective internal radiation therapy (SIRT) is rapidly increasing and the

3    need for quantification and dosimetry is becoming more widespread to facilitate treatment planning

4    and verification. The aim of this project was to develop an anthropomorphic phantom that can be

5    used as a validation tool for post-SIRT imaging and its application to dosimetry.

6    **Method:** The phantom design was based on anatomical data obtained from a T1 weighted volume

7    interpolated breath hold examination (VIBE) on a Siemens Aera 1.5 T MRI scanner. The liver, lungs

8    and abdominal trunk were segmented using the Hermes image processing workstation. Organ

9    volumes were then uploaded to the Delft Visualization and Image processing Development

10   Environment for smoothing and surface rendering. Triangular meshes defining the iso-surfaces were

11   saved as STL files and imported into the Autodesk® meshmixer software. Organ volumes were

12   subtracted from the abdomen and a removable base designed to allow access to the liver cavity.

13   Connection points for placing lesion inserts and filling holes were also included.

14   The phantom was manufactured using a Stratasys Connex3 polyjet 3D printer. The printer uses

15   stereolithography technology combined with ink jet printing. Print material is a solid acrylic plastic,

16   with similar properties to Polymethylmethacrylate (PMMA).

17   **Results:** Measured Hounsfield units and calculated attenuation coefficients of the material were

18   shown to also be similar to PMMA. Total print time for the phantom was approximately 5 days.

19   Initial scans of the phantom have been performed with Y-90 bremsstrahlung SPECT/CT, Y-90

20   PET/CT and Tc99m SPECT/CT. The CT component of these images compared well with the original

21   anatomical reference and measurements of volume agreed to within 9%. Quantitative analysis of the

22   phantom was performed using all three imaging techniques. Lesion and normal liver absorbed doses

23   were calculated from the quantitative images in 3 dimensions using the local deposition method.

24   **Conclusions:** 3D printing is a flexible and cost efficient technology for manufacture of

25   anthropomorphic phantom. Application of such phantoms will enable quantitative imaging and

26   dosimetry methodologies to be evaluated, which with optimisation could help improve outcome for

27   patients.

28

1    **Background**

2    Selective Internal Radiation Therapies (SIRT) with Y-90 microspheres is a radiotherapy option for the

3    treatment of liver tumours from both primary liver cancer (HCC) and liver metastases arising from

4    various primaries including colorectal and breast cancer.  Liver tumours are fed primarily with blood

5    flow from the hepatic artery while normal liver parenchyma is fed primarily from the portal vein (1).

6    To exploit this property, Y-90 microspheres are administered by injection through a trans-femoral

7    catheter positioned in the hepatic artery.  The microspheres, which are sized so as to lodge in the

8    neovascular rim of the lesion, are then selectively concentrated in the tumour following

9    administration.

10   The use of SIRT is rapidly increasing and the need for quantification and dosimetry is becoming more

11   widespread to facilitate treatment planning and verification (2).  Following administration of the

12   microspheres a SPECT-CT or PET-CT scan is performed to assess the Y-90 distribution.  Y-90

13   bremsstrahlung SPECT-CT scanning provides low image quality and poor quantitative accuracy  (3).

14   PET-CT can be used for Y-90 imaging with improved resolution (4) and higher accuracy for

15   quantification (5) than SPECT-CT.  However, the branching ratio for pair production is very low at

16   only $3.2 \times 10^{-5}$ resulting in long scan times and low count data.  Image analysis is generally performed

17   using relatively simple geometrical phantoms which are designed to evaluate given imaging

18   phenomena, characteristics or correction methods.  Anatomical phantoms are useful for providing a

19   more general qualitative and quantitative estimates of clinical image quality, or for analysis of

20   complex image processing regimens (such as a dosimetry protocol) (6-10). However, anatomical

21   phantom are generally more expensive and current commercial phantoms do not adequately represent

22   the microsphere uptake distributions observed in SIRT patients.  To better understand the merits of

23   imaging methodologies for Y-90 SIRT and the application of quantitative imaging for dosimetry a

24   phantom that represents the patient cohort would be greatly beneficial.

25   Recent work using rapid prototyping has demonstrated that 3D printing offers flexibility in design at a

26   reduced cost in comparison with traditional phantoms (10).  Commercially available printers are

27   generally based on three main techniques; thermoplastic extrusion, powder deposition and

28   stereolithography. Thermoplastic deposition uses a heated nozzle to extrude small beads of

1 thermoplastic material. As the material hardens new layers are built-up to create a three-dimensional

2 object. This method is employed in low cost printers but lacks the resolution and flexibility of some

3 of the other techniques. Powder deposition printers apply thin layers of binding material on the

4 printer tray and then coat this with a thin layer of powder. This process is repeated to build up the

5 powder/binder layers to create a 3D object. This technique generally offers higher resolution than the

6 extrusion technique. However, the final material is brittle and porous, requiring additional sealing for

7 long term use. Stereolithography based printers employ a vat of light-curable resin and a laser light to

8 build parts. The laser beam traces a cross-section of the object on the surface of the liquid resin.

9 Exposure to the laser light solidifies the pattern and joins it to the layer below, the resolution

10 achievable is of the order of a few microns and the final build material is more durable than other 3d

11 printing techniques. These printers are now used for final production parts and can produce fine

12 resolution structures on a sufficient scale to create bespoke molecular imaging test objects.

13 In this study we describe the design and manufacture of a bespoke phantom (Abdo-Man) for

14 quantitative imaging analysis of SIRT. A patient-realistic torso phantom was developed with liver

15 and lung organs and multi-positional lesions. The phantom is based on anatomical information

16 obtained directly from MRI data and printed using a Stratasys Connex3 3D printer.

17 **Methods**

18 (i) *Phantom design*

19 Key criteria in the design of the imaging phantom were considered. The phantom should be

20 anatomically realistic, and simulate a patient abdomen, both visually and when imaged with

21 scintigraphy and x-ray computed tomography. A fillable section within the structure was required to

22 represent activity distributions within a liver. The liver section needed to accommodate multiple

23 inserts for lesion representation, and allow flexibility in insert arrangement while allowing

24 reproducible assembly for repeated studies. All materials used in the phantom must have similar

25 densities and attenuation coefficients to tissue. The material for the lesions should also be transparent

26 for visualisation and ease of filling. Filling and assembly should be uncomplicated to reduce radiation

27 exposure when preparing the phantom. When filled the material should have low water absorption, be

28 water tight at all seals and sufficiently strong to maintain structural integrity when filled and

1 transported. Finally a total weight limit to the phantom was specified as 20 kg to ensure

2 transportation and manual handing constraints were met.

3 Mean liver volume of patients undergoing SIRT were taken from that measured by Theysohn et al

4 (11). The abdomen of a 32 year old male volunteer with an appropriate liver volume and anatomy

5 for representation of the patient cohort was then selected. Anatomical data were obtained from a 24

6 second T1 weighted volume interpolated breath hold examination (VIBE) on a Siemens Aera 1.5 T

7 MRI scanner, giving an in-plane pixel size of 0.7 mm and 2.8 mm contiguous slices. The required

8 organ volumes were generated from the anatomical dataset and converted to the appropriate file

9 format using a methodology similar to that previously described (10). Organs were delineated and

10 segmented on the Hermes, HybridViewer 2.2c image processing software (Stockholm, Sweden) to

11 create a new dataset containing only the required outlined volumes (liver, lungs and abdominal trunk).

12 Figure 1a and 1b show the original MR slice and segmented organ outlines. Organ volumes were

13 exported to the Delft Visualization and Image processing Development Environment (DeVide) (12)

14 for smoothing and surface rendering (Figure 1c). To remove the MR pixelation, the 3D surface mesh

15 was smoothed (Figure 1d) and saved as a binary STL file. The STL files were imported into the

16 Autodesk meshmixer software (Autodesk Inc) and the organ volumes subtracted from the abdominal

17 trunk, to create a fillable liver cavity. To ensure sufficient wall thickness in the phantom between the

18 liver and the lungs, the liver volume was relocated 5 mm in an inferior direction prior to subtraction

19 from the main body. A removable base was designed to allow access into the liver cavity and

20 connection points positioned for placing lesion inserts. A flow diagram illustrating the image

21 processing procedure is given in Figure 2, indicating the software tools used and data file type at each

22 processing step. Unlike previous designs (10), which use a modular assembly of fillable organ shells,

23 the solid abdominal trunk with liver void of the Adbo-Man phantom means the phantom is more

24 robust, and should be less prone to damage during transport and filling.

25 Spherical lesion inserts were designed for insertion into the finished phantom using the meshmixer

26 software. Spheres with diameters of 10, 20, 30, 40 and 50 mm were designed with 1mm wall

27 thicknesses. Spheres were designed to be connected to the base with detachable support rods which

28 attach to the spheres via connection ports with M6 screw fittings. 1 mm holes at the connection

1   points on the spheres allow the inserts to be emptied or filled with a 4 inch (102 mm) 19 gauge needle,

2   the hole is then sealed when the support rod is connected.   Figure 3 and Figure 4  illustrate the sphere

3   designs and how they are assembled within the phantom.   Once assembled the liver void can be filled

4   via an access port in the base of the phantom.   For consecutive acquisitions with varying

5   concentrations in the liver, addition activity can be added as necessary.  This procedure is quicker and

6   simpler than required by alternative designs whereby the phantom may need to be dismantled to

7   access the liver section.

8   In addition to simple spheres more complex inserts were also designed, including;

9       a)  40 mm hollow sphere with 25 mm solid inner sphere to represent the deposition of

10          microspheres in the neovascular rim of the tumour around a necrotic core

11      b)  40mm hollow sphere with the outer rim being divided into two compartments. This

12          represents lesions where arterial feeding happens through different arterial networks –

13          such as the left hepatic and right hepatic arteries.

14      c)  40 mm internal sphere where the external shell has a 1cm circular area which is entirely

15          blocked off. This simulates small regions of a lesion where microspheres are not

16          deposited.

17      d)  40 mm diameter hollow sphere,  1 mm wall thickness, with internal hollow sphere also

18          with 1mm wall thickness, internal diameter of 25 mm.   Each sphere can be filled

19          independently.

20   Schematic images of these inserts are shown in Figure 5

21   (ii)   *Phantom Production*

22   The phantom was printed using a Connex3 polyjet printer (Stratasys Ltd., Eden Prairie, MN, USA).

23   A 16 micron layer of liquid ultraviolet curable photopolymer is printed onto the build tray.   An

24   ultraviolet laser then cures the resin solidifying the pattern traced on the tray.   This process is then

25   repeated for each layer.  Where overhangs or domed shapes are required a removable support material

26   is printed on the under layers to prevent the structure collapsing before curing.  Various photopolymer

27   resins are available for printing; in this case a white opaque resin was chosen for the main phantom

28   body (VeroWhite Plus FullCure835). A black rubber-like material (TangoBlack Plus FullCure980

1  Shore 27a ) was printed alongside the main phantom material to create gaskets to seal the phantom

2  around the base and screw fittings.  Lesion inserts were printed using a transparent polymer,

3  (VeroClear FullCure810) to enable liquid level to be observed during filling.

4      (iii)  *Material Properties*

5  To test the suitability of the photopolymers prior to printing, material properties reported by the

6  manufacturer were compared to those more commonly used in phantom production.  In addition,

7  cubic test objects were printed and the density and CT Hounsfield units measured.  Composition of

8  the print material has previously been reported  as a mixture of acrylic monomers and oligomers, with

9  a small proportion ($< 2.5\%$) of a photo-initiator (10).  As the photo-initiator is subject to intellectual

10  property, no information regarding elemental composition is available.    An estimate of material

11  attenuation at isotope energies was estimated assuming that the monomer/oligomer mixture has a

12  similar effective atomic number to PMMA and substituting the unknown initiator for materials with

13  different effective atomic numbers as an input into the NIST X-COM program (13).  The effective

14  atomic number of the unknown initiator was increased until the outputted material attenuation

15  corresponded to that measured on CT.

16      (iv)  *Phantom Geometry*

17  To verify that the phantom was a true representation of the original anatomy, comparisons were made

18  against the original MR dataset.  Post production, the volume of water required to fill the phantom

19  was compared to the outlined volume measured on MR.  X-ray CT images of the phantom were also

20  acquired and a visual inspection of the CT and MR data sets performed.  Transaxial slices through the

21  liver section were compared and diametrical measurements of the liver and abdominal truck made

22  using the Hermes, HybridViewer 2.2c image processing software (Stockholm, Sweden).

23      (v)  *Phantom Imaging & Dosimetry*

24  To demonstrate the application of the phantom, multimodality imaging was performed with Y-90

25  SPECT/CT bremsstrahlung, Y-90 PET/CT and Tc99m SPECT/CT.  3 different lesion designs were

26  used within the phantom;  a 20 mm sphere, a 40 mm sphere and a 40 mm hollow sphere with 25 mm

27  solid inner sphere.  For the Y-90 imaging the liver section of the phantom was filled with 500 MBq of

28  Y-90 chloride, mixed with 0.2g of disodium ethylenediaminetetraacetic acid (EDTA) injection to

7

1     ensure a uniform mixture at 0.29 MBq/ml. Lesion inserts were filled with the appropriate

2     concentration of Y-90 solution (1.72 MBq/ml) to give a final liver to lesion concentration ratio of 1:6.

3     Y-90 activities were determined from a stock solution measured under calibration conditions with a

4     Fidelis secondary standard dose calibrator. Dilution activities and subsequent concentrations were

5     determined using accurate mass measurements made during dispensing. A similar procedure was

6     carried out to prepare the phantom for Tc99m imaging using a total activity of 200 MBq Tc99m

7     pertechnetate.

8     Y-90 PET/CT imaging of the phantom was performed as described by Willowson et al (14) on a

9     Siemens Biograph mCT scanner using a Na-22 isotope selection (as Y-90 was not an available

10     option). 2 bed positions acquired at 15 minutes were sufficient to cover the phantom length. Images

11     were reconstructed using an OSEM iterative reconstruction algorithm, 2 iterations 16 subsets, with

12     TOF and PSF correction. The final image size was a 200x200 matrix with 4 mm voxels smoothed

13     with a 4 mm Gaussian kernel.

14     Y-90 bremsstrahlung imaging was performed on a Siemens Symbia Intevo SPECT/CT scanner fitted

15     with medium energy general purpose collimators. Acquisitions were acquired with 72 projections at

16     20 s each. Energy window settings were chosen based on work by Heard et al (15) and covered an

17     energy range of 56 – 268 keV. Images were reconstructed with an OSEM iterative reconstruction

18     algorithm, 4 iterations and 8 subsets, with a PSF correction and CT attenuation correction. Ideally

19     PSF correction would be based on a measured bremsstrahlung PSF, however this was not available in

20     this version of reconstruction software. Instead a theoretical 2D Gaussian kernel, adjusted for septal

21     penetration is applied based on the centroid energy of the window and the medium energy collimator.

22     Tc99m SPECT/CT of the phantom was carried out to demonstrate the comparative image quality of

23     MAA over therapy imaging. SPECT/CT was performed using a similar protocol to the

24     Bremsstrahlung imaging using LEHR collimators and a 15% energy window centred at 140 keV.

25     Image analysis and absorbed dose calculations for all three lesions and imaging methodologies was

26     performed using the partition model (16) and in 3 dimensions using the local deposition method (17).

27     For the Bremsstrahlung and Tc99m imaging quantification was achieved using the total counts within

28     the liver and the known phantom activity. Quantification of the PET imaging was performed using

the inbuilt calibration factors and scaling the reconstructed image according to the known branching

ratio of Y-90 and Na-22.   Measured absorbed dose distributions were compared to a 'reference dose

distribution' derived from the known activity in each phantom compartment and the OEDIPE (18)

dosimetry interface tool for MCNPX2.5 Monte Carlo (MC) simulations.    Throughout all filling and

scanning protocols, finger and body TLDs were worn as standard practice.  No excess doses to the

operators were reported by the radiation dosimetry service.

**Results**

(i)    *Phantom design*

A photograph of the completed phantom is shown in Figure 6a-c.  The removable base with an

example arrangement of lesion inserts is shown in Figure 6d.

(ii)    *Phantom Production*

Material consumption and print time for the main phantom body, base and lesion inserts are

summarised in Table 1.  The total print time of any 3D object is dependent on size, and larger objects

took several days to print although as the printing process is automated this required no intervention.

The only restriction on this is the print cartridge size (3.6 kg) which required multiple changes for

printing of the larger objects. Material cost varies from €0.10 - 0.30 excluding VAT depending on the

material being printed.  Total production cost for the project was less than €11,000 which compares

favourably with costs of commercially available anthropomorphic phantoms.  Costs of printers vary

from €10k – €250k depending on printer size and material compatibility.  Bureau services are

available for outsourcing printing projects. However costs of material are often inflated.

**Table 1. Material consumption and print time for different organs and lesion inserts.**

| Organ | Material | Consumption (g) | Print time (h) |
|---|---|---|---|
| **Main Body** | Opaque (White) | 16309 | 109 |
| | Rubber-Like | 139 | |
| | Support | 2572 | |
| **Base** | Opaque (White) | 3480 | 38 |
| | Rubber-Like | 95 | |
| | Support | 424 | |
| **Lesions (Total)** | Transparent | 244 | 7 |
| | Support | 433 | |

1     (iii)    *Material Properties*

2 Measured HU, densities and estimated linear attenuation coefficients for common isotope energies are

3 summarised in table 2. No significant difference between the PMMA, transparent, and opaque

4 material was observed on CT, indicating an equivalent attenuation at the CT energy range ($\mu = 0.21$

5 $cm^{-1}$ at 60 keV). Material density was measured at 1.18 g/cm$^3$ for the solid materials and 0.9 g/cm$^3$ for

6 the rubber-like material. The lower density of the rubber material explains the lower HU of 96

7 measured for this material.

8                        **Table 2 X-ray properties of different materials.**

| Material | Density (g/cm3) | Measured HU | Attenuation coefficient (cm$^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 140 keV (Tc99m) | 171 keV (In-111) | 254 keV (In-111) | 365 keV (I-131) | 511 keV (PET) |
| **Water** | 1.00 | 0 | 0.15 | 0.14 | 0.13 | 0.11 | 0.096 |
| **Transparent** | 1.18 | 127 ± 15 | 0.17 | 0.16 | 0.15 | 0.13 | 0.110 |
| **Opaque (white)** | 1.18 | 127 ± 15 | 0.17 | 0.16 | 0.15 | 0.13 | 0.110 |
| **Rubber** | 0.90 | 96 ± 15 | 0.13 | 0.14 | 0.15 | 0.12 | 0.084 |
| **PMMA** | 1.18 | 126 ± 15 | 0.17 | 0.16 | 0.15 | 0.13 | 0.110 |

9 Physical properties of the print materials reported by the manufacturer are summarised in Table 3 and

10 Table 4 with comparison to other commonly used materials in phantom manufacture. The print

11 material was found to be less brittle than PMMA, and therefore less prone to shattering or breaking

12 under strain. Water absorption is reportedly higher than PMMA, so that it is more prone to swelling

13 when submerged. However this is still comparable to other plastic materials, such as nylon with water

14 absorption of up to 8.5 %. No discernible swelling or functional deformation in the material was

15 observed after submergence for 72 hours.

16              **Table 3 Physical properties of print material and other common plastics**

| Material | Tensile strength (MPa) | Elongation at break (%) | Modulus of elasticity (MPa) | Flexural Strength (MPa) | Water Absorption (%) | Rockwell hardness | Density (g/cm3) |
|---|---|---|---|---|---|---|---|
| Transparent | 50-65 | 10-25 | 2000 - 3000 | 75 -110 | 1.1 – 1.5 | M73-M76 | 1.17 - 1.18 |
| Opaque (white) | 50 - 65 | 10 -25 | 2000 – 3000 | 75 - 110 | 1.1 - 1.5 | M73 – M76 | 1.18 – 1.19 |

| | | | 2400 - 3400 | 82 - 117 | 0.3 | M80 – M100 | 1.18 |
|---|---|---|---|---|---|---|---|
| PMMA | 55 - 76 | 2 | | | | | |
| Nylon 6/6 | 85 | 90 | 2800 | 117 | 8.5 | M88 | 1.14 |

**Table 4  Physical properties of rubber print material and nitrile rubber.**

| Material | Tensile strength (MPa) | Elongation at break (%) | Compressive set (%) | Shore hardness | Tensile tear resistance (kg/cm) | Density (g/cm3) |
|---|---|---|---|---|---|---|
| Rubber-Like | 0.8 -1.5 | 170-220 | 4 -5 | A26 – A28 | 2 - 4 | 1.12 – 1.13 |
| Nitrile Buna Rubber | 1.4 – 17 | 350 - 650 | 30 | A65 | 4 | 1.20 |

(iv)    *Phantom Geometry*

Figure 7 shows coronal and sagittal CT slices through the phantom.  Transaxial CT images with the corresponding MR slice are given in Figure 8.  Measurement lines along the long and short axis of the liver and abdominal trunk are also given, the comparison results are summarised in Table 5.  The largest factor to affect variation in volume was generated when first smoothing the mesh to remove the image pixilation. The calculated volume of the smoothed liver and the printed phantom was less than 0.5%.  Despite the relative variation in volume between the original MR and phantom, this difference was considered acceptable as the voxelisation and freehand contouring would generate an uncertainty in the original measured organ volume.  The final liver volume remained consistent with the cohort average reported by Theysohn et al (11).

**Table 5.  Phantom dimension measurements compared to original MRI dimensions.**

| | Original MRI | Phantom | Difference (%) |
|---|---|---|---|
| Liver Volume (g) | 1972 | 1783 | 9.6% |
| Liver long axis (mm) | 215 | 212 | 1.4% |
| Liver short axis (mm) | 114 | 114 | 0.0% |
| Trunk anterior/posterior (mm) | 257 | 251 | 2.3% |
| Trunk left/right (mm) | 345 | 342 | 0.9% |

(v)    *Phantom Imaging & Dosimetry*

1    Figure 9a-c shows maximum intensity projections of the filled phantom imaged with Y-90 SPECT/CT

2    bremsstrahlung, Y-90 PET/CT and Tc99m SPECT/CT.  Figure 9d-f show the corresponding

3    transaxial SPECT and PET slices through the phantom fused with the CT data.  The transaxial slice

4    corresponds to a plane intersecting the 20 mm sphere and the 40 mm shell insert.

5    Measured lesions and liver activities calculated using the partition model are given in Table 6 for all

6    three imaging modalities with comparisons to the true activity measured during preparation.  It can be

7    seen that SPECT overestimates normal liver activity and underestimates lesion activity.  Of the three

8    imaging techniques, PET is the most accurate.

9    **Table 6. lesion and liver activities measured within the phantom calculated using the partition model and**

10   **compared to the true activity measured at preparation.**

|  | Activity (MBq) | | | |
|---|---|---|---|---|
|  | **Bremsstrahlung** | **PET** | **Tc99m SPECT** | **True** |
| 40 mm lesion | 30.8 | 51.3 | 50.7 | 56.9 |
| 40mm shell lesion | 21.3 | 37.2 | 33.7 | 41.2 |
| 20 mm lesion | 2.6 | 7.0 | 5.8 | 6.9 |
| Liver | 590.4 | 415.6 | 555.2 | 500.0 |

11

12   Cumulative dose volume histograms (cDVH) for the three lesions and entire liver volume generated

13   using local deposition for each quantified scintigraphy image are given in Figure 10 with comparisons

14   to that derived using MC and the known activity within each compartment.  In each example it can be

15   seen that both Tc-99m and bremsstrahlung imaging underestimate the absorbed dose.   This

16   underestimation can be contributed to errors in quantification that originate from delineation of the

17   liver volume.  For PET imaging the 50% cumulative dose volume is a better match for the MC

18   derived absorbed dose, indicating superior quantification. However, the shape of the cDVH is very

19   different and in this respect the Tc99m and bremsstrahlung is a better match.    All three imaging

20   modalities overestimate the absorbed dose delivered to the centre of the spherical shell lesion (Figure

21   10c).

22       **Discussion**

23   3D printing is an emerging field which has recently gained considerable media attention.  A number

24   of medical applications of 3D printing have been proposed including printing of orthodontic

1    appliances (19) prosthetic design (20) and surgical guides to teach, rehearse, and choose treatment

2    strategies (21).  Production of imaging test objects using rapid prototyping has also been suggested.

3    Harrison et al (22) used a computer numerical control (CNC) milling technique to produce a negative

4    mould used to cast a mixed density anthropomorphic radiotherapy phantom. However, the cost of this

5    approach is prohibitive and does not offer the flexibility of design alterations offered by 3D printing.

6    The main cost of the Abdo-Man phantom was due to the printing of a solid abdominal trunk.  This

7    design offered additional strength and ease of filling compared to a shell design, which would have

8    significantly reduced material cost.

9    Hunt et al (23) produced a QC phantom designed around the "porous phantom" by DiFilippo et al

10   (24).  The 3D printed phantom consisted of a cylindrical matrix of columns of decreasing width and

11   separations.  When filled with radioactive solution changes in the sub resolution columns produced a

12   phantom with sphere inserts of differing size and contrast.  However, the porous phantom is limited to

13   fixed geometry and prone to air bubbles and blockages.   Holmes et al (25) created a sub resolution

14   sandwich phantom by placing paper printed with radioactive ink between blocks of 3D printed

15   material.  An anatomical brain phantom was created whereby the source distribution could be altered

16   by changing the printed distribution on the paper.  This methodology allows for qualitative image

17   assessment.   However, exact source concentration is difficult to calculate and the printing and

18   assembly of the phantom is time consuming.

19   In this work a multi-compartmental anthropomorphic test phantom was developed, based on real

20   anatomy and specific to the patient cohort of interest.  The total print time for the phantom was

21   approximately 8 days.  Physical properties of the print material fulfilled the initial criteria and were

22   comparable to other commonly used materials.  The final structure was watertight, rigid and

23   sufficiently durable to withstand multiple assembly, transport and scanning protocols. To date the

24   phantom as undergone approximately 20 different acquisition protocols across different institution

25   sites and used by multiple operators.  The design of the phantom fulfilled the required brief in that the

26   anatomical detail was representative of the patient cohort and did not significantly differ in size or

27   shape from the original patient.  The liver design offered more flexibility for insert placement than

commercially available designs, yet allowed reproducible construction on reassembly, as demonstrated in Figure 9.

A potential application of the phantom has been demonstrated in a dosimetry study. Y-90 PET, SPECT and Tc99m SPECT images of the phantom were obtained and used to estimate absorbed doses to lesions and normal liver. The accuracy of the quantification was determined by comparing the measured activity with the known activity within the phantom measured at preparation. The corresponding absorbed dose map derived from the quantified images was compared against a true absorbed dose map generated using the known activity and Monte Carlo simulations. Like most commercial dosimetry software, image quantification was achieved using the partition model which is dependent on the operator's ability to outline the liver volume. The complex anatomical shape of the Abdo-Man liver therefore allowed for a more accurate representation in outlining and hence quantification accuracy compared to that using a geometric alternative. The dosimetry results presented are designed to demonstrate the application of the phantom and further investigation would be required to validate these initial findings and potentially optimise the methodologies for improved quantification and absorbed dose accuracy. In future work the phantom will be used to analyse a number of commercial SIRT dosimetry software packages and investigating possible improvements in quantification with alternative reconstruction algorithms, such as the Siemens X-SPECT and Hermes SUV-SPECT software.

The phantom is the first in a range of "Abdo-Man" phantoms to be developed for this application and unlike conventional manufacturing techniques (which require expensive tooling for mass production) design alterations can easily be implemented before the next phantom is printed. In the future, design evolutions of the phantom are planned; these will include simulation of lung shunts and the addition of lobular cavities within the liver section. Further work is also being undertaken to incorporate bone mimicking materials. Other applications where this technology could be employed include manufacturing phantoms for use in preclinical scanners, replacement parts for old phantoms and dosimetry phantoms for external beam radiotherapy (in combination with polymer gel technology) (26). 3D printing offers additional flexibility in design and reduced costs compared to conventional

manufacturing techniques. Wider and more routine applications of such phantoms will allow for treatment validation and optimisation and lead to improved outcome for patients.

**Conclusion**

An anthropomorphic test phantom based on real patient anatomy and specific to the patient cohort of interest has been manufactured using a 3D printer. The final phantom meets the initial design criteria and the production material is comparable to standard materials. Production time and cost is significantly reduced compared to standard methods and designs can offer more flexibility than those previously available. This technology is suitable for a number of applications and its future use for phantom manufacture could become routine.

**Ethics Approval and Consent to Participate**

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants involved in the study

**Competing Interests**

The authors declare that they have no competing interests

**Authors contributions**

JG, GF and MT conceived of and designed the study. JG, CC and CL designed and manufactured the phantom. JG and AC carried out the imaging experiments. AD carried out the Monte Carlo simulations. JG and AC analysed and interpreted the data. JG drafted the manuscript. All authors critically revised and approved the final manuscript.

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