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Note

Quasi-simultaneous 3D printing of muscle-, lung- and bone-equivalent media: a proof-of-concept study

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Abstract 3D printing is a promising solution for the production of bespoke phantoms and phantom components, for radiotherapy dosimetry and quality assurance (QA) purposes. This proof-of-concept study investigated the use of a dual-head printer to deposit two different filaments (polylactic acid (PLA) and StoneFil PLA-concrete (Formfutura BV, Nijmegen, Netherlands)) at several different in-fill densities, to achieve quasi-simultaneous 3D printing of muscle-, lung- and bone-equivalent media. A Raise 3D Pro 3D printer (Raise 3D Technologies Inc, Irvine, USA) was used to print one thoracic and one cranial phantom slab. Analysis using in-house 3D print QA software showed that the two humanoid phantom slabs geometrically matched the stereolithography (STL) files on which they were based, within 0.3 mm, except in one area of the thoracic slab that was affected by thermal warping by up to 3.4 mm. The 3D printed muscle, lung and bone materials in the two humanoid phantom slabs were approximately radiologically-equivalent to human muscle, lung and bone. In particular, the use of StoneFil with a nominally constant in-fill density of 100% resulted in regions that were approximately inner-bone-equivalent, at kV and MV energies. These regions were bounded by walls that were substantially denser than inner bone, although generally not dense enough to be truly...
cortical-bone-equivalent. This proof-of-concept study demonstrated a method by which multiple tissue-equivalent materials (eg. muscle-, lung- and bone-equivalent media) can be deposited within one 3D print, allowing complex phantom components to be fabricated efficiently in a clinical setting.

**Keywords** Radiation therapy · 3D printing · additive manufacture · rapid prototyping

1 Introduction

Over the last five years, 3D printing (specifically rapid prototyping using an additive manufacture technique) has emerged as a promising solution for the production of bespoke phantoms and phantom components, for radiotherapy dosimetry and quality assurance (QA) purposes [1,2]. Numerous authors have experimented with the use of different 3D printing filaments and in-fill densities, with the aim of producing solid structures that are radiologically equivalent to human tissues (see Tino et al [1] for a detailed review of these efforts). For example, the printing of approximately lung-equivalent materials has been demonstrated using high-impact polystyrene (HIPS) filament at an in-fill density of 60% [3], acrylonitrile butadiene styrene (ABS) filament [4] and polyactic acid (PLA) filament [5], both at an in-fill density of 30%, as well as PLA filaments infused with wood fibres at in-fill densities from 30% [6] to 90% [5]. The printing of approximately water-, muscle- and solid-tumour-equivalent materials has been demonstrated using ABS and PLA at in-fill densities from 80% to 100% [4–9]. Creation of bone-equivalent materials using 3D printing methods has proved more challenging, with bone often omitted from 3D printed phantoms [4,10–13] or modelled using materials that differ from the surrounding soft tissue just enough to be visible in a computed tomography (CT) image [14,15].

Generally, researchers who have created composite phantoms containing different materials have done so by printing those materials as separate pieces and then combining them together to produce the finished phantom (eg. lung containing solid tumour [4,6], tissue containing lung [16], thorax containing lung and bone [15], neck and shoulders containing vertebral bodies [17], pelvis containing pelvic organs [12]). For convenience, however, and to allow straightforward fabrication in a clinical setting, it would be ideal to be able to print multiple tissue-equivalent materials simultaneously, so that all materials were deposited at the same time, or quasi-simultaneously, so that each layer of a given 3D print could contain materials that model different human tissues.

One previous example of the fabrication of QA phantoms using a quasi-simultaneous multi-material 3D printing method can be found in the work of Solomon et al, who used a multi-material resin printer to generate cylindrical test objects that were used to evaluate CT reconstruction algorithms [18]. Solomon et al’s method involved printing with mixtures of plastic resin that varied in density over a short geometric range (tens to hundreds of microns). In-house code was used to generate 3D printing instructions that assigned specific
3D printing of radiotherapy phantoms

The materials used by Solomon et al. were two photo-polymer resins with similar densities (approximately 1.15 and 1.18 g/cm$^3$), which were useful for evaluating low contrast detectability in CT images [18].

For use in radiotherapy QA, it would obviously be useful to extend the range of densities printed, to include lung- and bone-equivalent media, while also designing phantoms that are more geometrically similar to human anatomy. In a clinical context, it would also be desirable to avoid the use of materials that produce fumes during printing (including resins) [19], especially materials that produce comparatively high levels of volatile organic compounds (such as ABS) [20], and to preferentially use materials that produce comparatively low levels of ultra-fine particles during printing (such as PLA) [21].

This proof-of-concept study therefore investigated the use of a dual-head printer to deposit two different PLA-based filaments at several different in-fill densities, in order to achieve quasi-simultaneous 3D printing of muscle-, lung- and bone-equivalent media, for use in radiotherapy QA phantoms.

2 Methods

2.1 3D printing hardware

All 3D printed objects used in this study were fabricated using a Raise 3D Pro 3D printer (Raise 3D Technologies Inc, Irvine, USA). This printer has two extruders with retractable print heads and is therefore capable of printing single objects using two different 3D printing filaments.

To print test objects containing lung-, muscle- and bone-equivalent materials, two different filaments were used. PLA filament was used, at two different in-fill densities, to model lung and muscle, and StoneFil PLA-concrete filament (Formfutura BV, Nijmegen, Netherlands) was used to model bone. The StoneFil filament was made from 50% PLA and 50% powdered stone, by weight, and was therefore expected to produce a print density substantially greater than PLA with radiological properties similar to bone.

As an initial test of the performance of the printer and the filaments, when used to produce multi-material objects, a simple test object was designed using TinkerCAD software (Autodesk Inc, San Rafael, USA). A 6 × 6 × 2 cm$^3$ block was defined, as a simple model of chest wall muscle. A cylinder was placed along the inside of one side of the block, as a simple model of a vertebra, and two spheres were added, to represent a right and left lung. This model was then exported from TinkerCAD as three stereolithography (STL) files, separately defining the geometry of the muscle, lung and bone.

The STL files were then imported into the IdeaMaker software package (Raise 3D Technologies Inc, Irvine, USA), where the gcode instructions for the 3D printer were created. The IdeaMaker software was used to select the Raise 3D Pro dual head printer as the printing hardware, assign the bone structures to one of the printer’s two extruders, assign the lung and muscle
structures to the other extruder and define the infill density of the print in the three structures. Based on previous work by Kairn et al [4] and Dancewicz et al [5], infill densities of 100% and 50% were respectively selected, for modelling muscle and lung tissue using PLA. An infill density of 100% was used to model the bone using StoneFil PLA-concrete filament.

2.2 3D model design

Two simple phantom slabs were designed for the purpose of investigating and demonstrating the multi-material printing process; one thoracic phantom slab and one cranial phantom slab. Broadly, designs for these humanoid slabs were created by defining structures using CT data with the 3D Slicer software package [22], exporting those structures as STL files, and then using Raise 3D’s IdeaMaker software to create the final gcode for the 3D printer using the exported STL files. Some additional steps were performed differently for the two humanoid phantom slabs, as described below.

In order to base a simple humanoid phantom on realistic thoracic anatomy, anonymized CT data was acquired from the public repository of the Cancer Imaging Archive [23]. A sample DICOM CT dataset (AMC-002-18-1992-CT THORAX-01630) [24,25] was downloaded for use in this study. Within the 3D Slicer software, thresholds were used to segment the CT data into structures defining the regions occupied by three tissue types (muscle, lung and bone), which were exported as three separate STL files.

Before preparation in IdeaMaker, the three STL files defining the thoracic structures were imported into MeshMixer (Autodesk Inc, San Rafael, USA) for further processing. At this stage, a decision was made to simplify the model, for this proof-of-concept study, given that we were not yet sure whether our proposed method would produce successful results. Rather than expending a large amount of time and filament, by printing an entire thorax, the model was simplified and re-scaled, to produce a 19.7×19.7×1.0 cm$^3$ slab that could be fitted into an existing square, water-equivalent QA phantom, for further testing. To produce this externally-rectilinear phantom, a 19.7×19.7×1.0 cm$^3$ slab was created in TinkerCAD and imported into MeshMixer. Within MeshMixer, Boolean operations were used to crop the lung and bone structures to fit within the slab. At this stage, the STL file containing the muscle structure from 3D Slicer was abandoned and replaced with the 19.7×19.7×1.0 cm$^3$ slab, which became the new “muscle” structure. The lung and bone structures were also smoothed (smoothing factor 5) and repaired in Meshmixer, to ensure that there were no gaps or non-manifold meshes in the structures, before all three new structures were exported as STLs for conversion to gcode by IdeaMaker.

As an extension of this work, the cranial slab was designed to fit within a sophisticated, heterogeneous phantom. To that end, rather than using human CT data, the CIRS 601 head phantom (Standard Imaging Inc, Middleton, USA) was CT scanned using a Siemens Somatom Confidence CT scanner (Siemens AG, Erlangen, Germany) operating at 120 kVp, with the cranial
section of the phantom separated from the head-and-neck section of the phantom by a consistent gap created by small plastic blocks. Using this CT data, the external surface of the phantom was contoured in one CT slice above and below the gap and interpolated to produce a soft-tissue structure for printing. The skull bones were similarly contoured in one slice above and below the gap, interpolated and manually edited to produce a bone structure for printing. All contouring, interpolating and editing was performed using 3D Slicer and the resulting structures were exported as STLs for final preparation and gcode production by IdeaMaker.

Like the test block, the tissue, lung and bone structures in the thoracic phantom slab were selected for printing respectively using PLA with an in-fill density of 100%, PLA with an in-fill density of 50% and StoneFil filament with an in-fill density of 100%. For simplicity, all soft tissues in the cranial phantom slab (including brain, adipose, muscle and skin) were printed as “muscle” and all cranial bones were printed as bone, using similar settings to the thoracic slab (see table 1).

Table 1 Summary of 3D printing parameters used to create the different media in the humanoid phantom slabs.

| Phantom   | Medium   | Material | In-fill | No. walls |
|-----------|----------|----------|---------|-----------|
| Thorax slab | Lung     | PLA      | 50%     | 3         |
| Thorax slab | Muscle   | PLA      | 100%    | 3         |
| Thorax slab | Bone     | StoneFil | 100%    | 3         |
| Head slab  | “Muscle” | PLA      | 95%     | 2         |
| Head slab  | Bone     | StoneFil | 100%    | 7         |

The cranial phantom slab was also printed with a 1.5 mm thick, latticed raft between the print and the print bed, after thermal warping effects were observed affecting the print of the thoracic slab (described in the results section). The use of a brim (or localised brims such as “mouse ears” at the corners of the print [26]) for this purpose was considered as a means to reduce the time and filament required for printing, but the raft solution was chosen after some reflection upon our local experience with both methods; we have previously found that rafts avoid thermal warping effects more effectively than brims, for the particular 3D printer and filaments used in this work.

One final modification was added to the cranial slab design, after observing the results of the thoracic slab print. A change was made to the number of walls (also known as “perimeters” or “shells”, depending on 3D printing software) that were used to surround and contain each medium, so that more walls were used for the bone regions and slightly fewer walls were used for the “muscle” regions (see table 1).
2.3 3D printing process

To print the $6 \times 6 \times 2$ cm$^3$ test block, the thoracic phantom slab and the cranial
phantom slab, using PLA and StoneFil filaments from the dual heads of the
Raise 3D Pro printer, the print temperature was set to 215°C for both heads
and the print bed was maintained at 60±10°C throughout all print processes.

The manufacturer’s recommendations were followed for levelling (tram-
ming) the print bed. A feeler gauge and a calibration print (thirteen thin
squares printed at regular intervals across the print bed) were used to verify
accurate bed levelling.

Total print times were within 6 h for the test object (total volume 72 cm$^3$),
16 h for the thoracic phantom slab (total volume 388 cm$^3$) and 19 h for the
cranial phantom slab (total volume 261 cm$^3$). These print times were achieved
by using an extrusion width (determined by nozzle diameter) of 0.4 mm with
a layer thickness of 0.3 mm.

The print of the cranial phantom slab failed twice, requiring restarting.
The first of these failures resulted from excessive heating of the print heads
leading to plastic melting and blocking the extrusion system. This unexpected
problem was attributed to the process of alternating between print heads,
which requires each head to maintain its 215°C temperature, keeping the fila-
ment hot but not extruding, while waiting for the other head to complete its
part of each print layer. Although numerous methods for managing thermal ef-
fects during 3D printing have been proposed [26], our issue was resolved very
simply, after un-blocking both extruders, by taking the top of the external
plastic housing off the printer to allow more air circulation around the system.
The other failure was due to simple tangling of the StoneFil filament due to
manual handling of the filament prior to use. The tangle caused the Stone-
Fil filament to become stuck, resulting in the complete printing of a tissue
slab containing only air where the bone should be. This issue was resolved by
simply de-tangling and re-winding the filament.

2.4 3D print evaluation

The $6 \times 6 \times 2$ cm$^3$ test block was evaluated qualitatively during the printing
process, to identify whether the different volumes were being printed by the
correct print heads (using the correct materials) and whether the 50% in-fill
volumes appeared to be printed using a lower in-fill density than the 100% in-
fill volumes. After printing, the test block was examined using kV CT imaging,
using the Siemens CT scanner, to verify that all internal volumes were printed
using appropriate densities and that there were no internal air gaps or fissures.

The humanoid phantom slabs were evaluated more qualitatively, starting
with the completion of 3D print QA tests using in-house software [27], based
on a method described by Sasaki et al [28]. These tests used high-resolution
(narrow field-of-view) kV CT scans of the prints, with each slab lying flat
on top of a radio-transparent block, so that the QA software was able to
use Hounsfield unit (HU) gradients and thresholds to automatically identify each print within the CT image. The software was then able to produce a histogram of the HU values in each slab and output a new STL file describing its surface, for comparison with the STL file from which the slab was printed. The qualitative comparison between the STL file produced from each printed slab and the STL describing the planned surface of the print was performed using a Hausdorff distance map via Meshlab software [29,30].

Additional kV CT scans of the two humanoid phantom slabs were produced with each slab standing in the transverse plane, between pre-existing phantom components that acted as a source of scatter for the CT imaging beam and mimicked the setup that would be used if each slab print was duplicated and adopted for use in dosimetry and QA testing of the local radiotherapy treatment planning system. Specifically, the thoracic slab was placed between sheets of RW3 water-equivalent plastic (PTW, Freiburg, Germany) and the cranial slab was placed between the cranial section and the head-and-neck section of the CIRS 601 head phantom. CT images of the printed slabs in these configurations were used to identify mean HU values (and standard deviations) in the lung, bone and muscle regions of the humanoid phantom slabs, under equivalent scatter conditions to their expected clinical use.

To evaluate the tissue-equivalence of the materials in the humanoid phantom slabs, for a megavoltage photon beam, the nominal 3.5 MV imaging beam from a Hi-Art TomoTherapy unit (Accuracy Inc, Sunnyvale, USA) was used to obtain MV CTs of the slabs, standing in the transverse plane between phantom components, in the same setup as used for the kV CT scans described above. The same analysis steps that were applied to the kV CT images were applied to the MV CT images, to obtain mean HU values (and standard deviations) in approximately the same regions of interest as were used for the kV CT images.

Local HU-density and HU-relative-electron-density calibration data from this particular Siemens kV CT unit and TomoTherapy MV CT unit were then used to convert all of the mean HU values obtained from the respective kV CT and MV CT scans, to derive material densities in the 3D prints that could be compared against published densities of human tissues [31,32]. This method provided an indication of the tissue-equivalence of the 3D printed phantom materials under kV imaging, MV imaging and potentially MV radiotherapy treatment conditions.

3 Results

3.1 Qualitative evaluation of initial test block

Figures 1(a) to (c) illustrate the results of the qualitative evaluations of the simple, multi-material test block. Figure 1(a) shows the test block during printing of the lung region; the right print head is extended to print PLA, the left head is retracted, and the low-density mesh is visible below right print
head. Figure 1(b) shows the test block during printing of the bone region; the left print head is extended to print StoneFil, the right head is retracted, and the StoneFil area is visible below left print head. Examination of these characteristics during the process of printing the test object suggested that the process was proceeding successfully, achieving a single print using different materials and different densities.

Figure 1(c) shows a slice from the kV CT scan of test object, which confirms that a reduced in-fill density was used to print the lung test regions and that the 100% in-fill region printed using StoneFil achieved a substantially higher HU value than the 100% in-fill regions printed using PLA, suggesting that these materials and densities may be suitable for modelling lung, bone and muscle, in more-complex humanoid phantom prints.

3.2 Quantitative evaluation of humanoid phantom slabs

Results of testing the two humanoid phantom slabs using our in-house 3D print QA system are shown in figures 2(a) to (d). The HU histogram shown in figure 2(a) shows the broad range of HU values found in the thoracic phantom slab, indicating that lung-equivalent (HU \(\leq -400\) for this CT scanner) and bone-equivalent (HU \(\geq 180\) for this CT scanner) materials were present, in addition to a large proportion of muscle-equivalent plastic (HU \(\approx 0\)).

The Hausdorff distance render of the thoracic phantom slab in figure 2(b) shows a substantial region of disagreement between the external shape of the printed humanoid slab and the surface of the STL design on which it was based. The photograph shown in figure 3(a) shows the warped region in the lower right hand corner of the image. This warping of one corner of the print probably resulted from uneven contraction of the print during cooling, due to inconsistent heating of the print bed or inconsistent contact between the print and the heated bed [13]. The Hausdorff distance analysis (figure 2(b)) indicated that the warped corner disagreed with the planned geometry by up to 3.4 mm, while disagreement throughout the result of the print was within 0.3 mm.
Fig. 2  (a) Histogram of HU values within the thoracic slab print.  (b) Screenshot of Hausdorff distance comparison from Meshlab for the thoracic slab print.  (c) Histogram of HU values within the cranial slab print.  (d) Screenshot of Hausdorff distance comparison from Meshlab for the cranial slab print.  (In (b) and (d) agreement within 0.3 mm is shown as green and disagreement greater than 3 mm is shown as red.)

Fig. 3  Images of humanoid phantom slabs:  (a) photograph of thoracic slab; transverse slices through (b) kV CT and (c) MV CT of thoracic slab; (d) photograph of cranial slab; (e) photograph of cranial slab within head phantom; and sagittal slices through (f) kV CT and (g) MV CT of cranial slab.  Arrows indicate (a) warped region of thoracic slab, (f) location of cranial slab in kV CT and (g) location of cranial slab in MV CT.
Results of testing the cranial phantom slab using our in-house QA system are shown in figures 2(c) and (d), where it is apparent that a large proportion of the material in the cranial slab was printed at soft-tissue densities (HU ≈ 0), but appreciable proportions of the slab were also printed at inner bone (up to 210 HU for this CT scanner) and denser bone (400-800 HU for this CT scanner) densities. A minimal proportion of this phantom slab could be considered equivalent to cortical bone (800-1200 HU for this CT scanner).

The cranial slab showed no thermal warping (see figures 2(d) and 3(d) and (e)), possibly due to the use of a raft during printing. A Hausdorff distance comparison showed that all points on the surface of the cranial slab print agreed with the planned geometry within 0.2 mm (figure 2(d)).

Issues leading to the respective < 0.3 mm and < 0.2 mm geometric difference between the phantom slabs and their corresponding STL surfaces included difficulty in levelling the slabs during acquisition of the kV CT images used by the in-house 3D print QA software (most obvious in figure 2(b)) and a very slight (< 0.1 mm) difference in surface height between the bone and tissue regions (visible in both figure 2(b) and 2(d))). While our in-house QA system detected these differences, they were not apparent on visual or tactile observation of the surfaces of the print and did not affect the fit between each slab and the commercial phantom for which it was designed (for example, see figures 3(f) and (g)).

The results of analysing the HUs and densities of the materials in specific regions of interest in the humanoid phantom slabs, as derived from the kV CT and the MV CT images of the phantom (shown in figures 3(b), (c), (f) and (g)), are listed in tables 2 and 3, respectively. Comparison of the data in these tables indicates that there is good agreement, within uncertainties, between the densities determined using kV and MV imaging for the materials used to model lung, inner bone and cortical bone, although a noticeable difference is present for muscle. These results also provide an indication of the degree of tissue- and bone-equivalence achieved in specific regions of the phantom slabs, when irradiated using kV and MV photon beams.

| Phantom  | Medium       | Phantom HU | Phantom $\rho_e/\rho_{e,\text{water}}$ | Phantom $\rho_m$ | Tissue $\rho_m$ |
|----------|--------------|------------|----------------------------------------|------------------|----------------|
| Thorax slab | Lung      | -550±70    | 0.44±0.06                              | 0.45±0.06        | 0.19 to 0.36 [31] or 0.26 [32] or 0.45 [33] |
| Thorax slab | Muscle    | 10±20      | 0.90±0.02                              | 0.94±0.02        | 1.05 [32]      |
| Thorax slab | Inner bone | 330±40     | 1.16±0.03                              | 1.22±0.03        | 1.18 [32]      |
| Thorax slab | Cortical bone | 630±100 | 1.41±0.09                              | 1.48±0.09        | 1.92 [32]      |
| Head slab  | "Muscle"   | -10±30     | 0.88±0.02                              | 0.92±0.02        | 1.05 [32]      |
| Head slab  | Inner bone | 300±30     | 1.14±0.02                              | 1.20±0.02        | 1.18 [32]      |
| Head slab  | Cortical bone | 570±80  | 1.36±0.06                              | 1.43±0.07        | 1.92 [32]      |
Table 3: Table of HU and density results from MV CT of humanoid phantom slab, listing the mean (± one standard deviation) HU values, derived relative electron densities ($\rho_{e}/\rho_{e,\text{water}}$) and derived mass densities ($\rho_{m}$, in g/cm$^3$) within regions of interest within the different simulated media, alongside published $\rho_{m}$ values for these tissue types.

| Phantom  | Medium     | Phantom HU | Phantom $\rho_{e}/\rho_{e,\text{water}}$ | Phantom $\rho_{m}$ | Tissue $\rho_{m}$ |
|----------|------------|------------|------------------------------------------|--------------------|------------------|
| Thorax slab | Lung       | -530±50    | 0.45±0.05                                | 0.47±0.06          | 0.19 to 0.36 [31] or 0.26 [32] or 0.45 [33] |
| Thorax slab | Muscle     | 20±40      | 1.00±0.04                                | 1.06±0.04          | 1.05 [32]        |
| Thorax slab | Inner bone | 100±40     | 1.09±0.04                                | 1.15±0.04          | 1.18 [32]        |
| Thorax slab | Cortical bone | 250±80   | 1.25±0.06                                | 1.32±0.06          | 1.92 [32]        |
| Head slab  | “Muscle”   | -5±30      | 0.99±0.03                                | 1.04±0.04          | 1.05 [32]        |
| Head slab  | Inner bone | 130±20     | 1.13±0.02                                | 1.19±0.02          | 1.18 [32]        |
| Head slab  | Cortical bone | 240±30  | 1.24±0.03                                | 1.31±0.03          | 1.92 [32]        |

4 Discussion

Having completed a small test print, and after two false starts, this study developed and verified a method for using a dual-head printer to deposit two different filaments at different in-fill densities. This method was demonstrated by printing two humanoid phantom slabs for potential use in radiotherapy dosimetry or QA applications. The method was shown to allow multiple tissue-equivalent materials (eg. muscle-, lung- and bone-equivalent media) to be deposited within one 3D print, allowing complex phantom components to be fabricated efficiently in a clinical setting.

The HU histogram shown in figure 2(a) shows the large proportion of the volume of the thoracic slab that was taken up by muscle-equivalent plastic (HU≈0). While most of the volume of a healthy thorax would be taken up by low-density lung, the choice of an unhealthy thorax CT (with substantial lung invasion by tumours and fibrosis) and the decision to print the corners of the phantom (outside the external skin contour) using unit density PLA as shown in the photograph in figure 3(a), has resulted in a smaller proportion of low-density material within this slab, as shown in the CT slices in figures 3(b) and (c). Figure 2(a) also shows that there is a substantial spread of HU values beyond the range expected for lung tissue (HU from -500 to -700 for this CT scanner), possibly due to the use of a grid in-fill pattern.

The simplicity of these “humanoid” slab models was an obvious limitation of this study; only one slab included low density (lung) regions and only the other used a humanoid external contour and a one-to-one scale. While printing phantoms as blocks or slab sections is a useful method to produce adaptable phantoms [34] while avoiding issues with print area limitations [13], in this case the resulting slabs have minimal obvious utility. Ultimately these slabs may be duplicated, to accommodate radiochromic film, or augmented with slabs containing space for ionisation chambers or dosimetry diodes, but such work was beyond the scope of this 3D-printing-focussed proof-of-concept study.
The densities derived from kV CT and MV CT images of the material used
to model lung agreed with each other, within uncertainties (0.45±0.06 g/cm$^3$
from kV CT and 0.47±0.06 g/cm$^3$ from MV CT, see tables 2 and 3), but ex-
ceeded the lung density reported by the International Commission on radiation
Units and Measurements (ICRU Report 44), based on physical measurements
of ex vivo samples of lung tissue [32] as well as the range reported by van Dyk et
al based on early kV CT measurements [31], and instead matched the density
of the plastic used to model lung in a contemporary CT calibration phantom,
0.45 g/cm$^3$ [33]. This agreement with the CT calibration phantom rather than
the human tissues is an obvious result of the method by which the PLA in-fill
density was chosen, specifically with reference to previous publications that
verified lung-equivalence with reference to commercial plastic phantoms [4,5].
To improve agreement with the published lung tissue densities, a reduced in-
fill density may be needed, although this would require a sparser in-fill pattern
[4] which might best be achieved by using gyroid structures rather than a grid
pattern [35].

For muscle, the results in tables 2 and 3 from using the thoracic slab and the
cranial slab agree with each other, although all muscle densities derived from
the kV CT images were slightly lower than expected. The densities derived
from MV CT images, 1.06±0.04 g/cm$^3$ for the thoracic slab and 1.04±0.04
g/cm$^3$ for the cranial slab, agreed within uncertainties with the density of
human skeletal muscle that has been reported based on physical measurements
[32], 1.05 g/cm$^3$, suggesting that this material can be regarded as muscle-
equivalent in an MV imaging beam and therefore potentially also in an MV
radiotherapy treatment beam.

Although achieving bone-equivalence was a challenging goal for this small
proof-of-concept study, promising results were achieved. Firstly, the densities
of the inner-bone regions in the rib, vertebra and skull in the 3D printed slabs
all agreed with each other and with the published density of human spongiosa
[32], when imaged using both the kV CT and the MV CT systems (see tables
2 and 3), suggesting inner-bone-equivalence for both kV and MV photons.
Secondly, the densities of the walls around the bone regions in both humanoid
slabs were measured as substantially greater than the densities within the bone
regions, although not as great as the reported density of human cortical bone
(see tables 2 and 3 and figure 2(a) and (c)). The densities in these bone wall
regions also agreed with each other within uncertainties when derived from
both kV CT and MV CT data (see tables 2 and 3).

The difference between the densities of the inner regions of the 3D printed
bones and the densities of the walls that surrounded them, all of which were
printed using StoneFil at a nominal in-fill density of 100%, points to an inconsis-
tency in the way that the Raise 3D printing system interprets “100%” when
printing different parts of an object. This inconsistency was advantageous in
this study (allowing inner bone and dense bone to be printed in a compara-
tively realistic arrangement) but should be the subject of further examination,
especially if different 3D printing systems are use to repeat or build upon this
work.
Finally, the agreement observed in this study between the kV CT and MV CT density results for the bone regions is particularly important, given the recently reported practice of modelling bone for diagnostic (kV) imaging purposes by 3D printing with ABS filaments that have been doped with barium sulphate or bismuth [1,36,37]. Plastics doped with barium (Z=56) and bismuth (Z=83) are able to produce a bone-like appearance when imaged at kV energies [36,37] due to photoelectric enhancement, but are likely to behave equivalently to soft tissue rather than bone when imaged or irradiated at MV energies, due to their electron densities remaining similar to plastic [38]. By contrast, the calcium-based composite used in the StoneFil concrete filament that was investigated in this study enables this particular filament to replicate the attenuation and scatter characteristics of bone, with interaction cross-sections that are consistent with human bone across the kV-MV energy range.

5 Conclusion

This proof-of-concept study demonstrated that heterogeneous phantoms or phantom components can be fabricated by depositing different filaments at different in-fill densities during continuous 3D printing processes. As an example, quasi-simultaneous 3D printing of muscle-, lung- and bone-equivalent media was demonstrated by using PLA at 100% in-fill, PLA at 50% in-fill and StoneFil concrete at nominally 100% in-fill to produce materials that were radiologically equivalent to human muscle tissue at MV energies, radiologically equivalent to a commercial plastic used to model human lung tissue at kV and MV energies and radiologically equivalent to inner bone as well as a denser form of bone (albeit largely less dense than human cortical bone) at kV and MV energies.

The method of producing single prints containing different filaments with different densities that was demonstrated in this study should allow complex phantoms and phantom components to be fabricated efficiently in a clinical setting. This study used just two different filaments that were printed at a small number of nominal densities, but the techniques used for this work could obviously be used to print using larger numbers of nominal in-fill densities and could be extended to allow quasi-simultaneous or even simultaneous printing of numerous materials as 3D printing technologies improve and costs decrease.

6 Compliance with ethical standards

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Ethical approval: This article does not contain any studies with human participants performed by any of the authors.
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