Not all 3D-printed bolus is created equal: Variation between 3D-printed polylactic acid (PLA) bolus samples sourced from external manufacturers

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Abstract

Introduction: Polylactic acid (PLA) is a promising material for customised bolus 3D-printing in radiotherapy, however variations in printing techniques between external manufacturers could increase treatment uncertainties. This study aimed to assess consistency across various 3D-printed PLA samples from different manufacturers. Methods: Sample prints of dimensions 5 × 5 × 1 cm with 100% infill were acquired from multiple commercial 3D-printing services. All samples were CT scanned to determine average Hounsfield unit (HU) values and physical densities. The coefficient of equivalent thickness (CET) was obtained for both photons and electrons and dose attenuation compared to TPS calculations in Elekta Monaco v5.11. Results: Some samples showed warped edges up to 1.5 mm and extensive internal radiological defects only detectable with CT scanning. Physical densities ranged from 1.06 to 1.22 g cm\(^{-3}\) and HU values ranged from 5.1 to 221.0 HU. Measured CET values varied from 0.95 to 1.17 and TPS dose calculations were consistent with the variation in CET. Electron R50 and R90 shifted by up to 2 mm for every 1 cm of printed bolus, a clinically significant finding. Photon surface dose varied by up to 3%, while depth doses were within 1%. Conclusions: 3D-printed PLA can have considerable variability in density, HU and CET values between samples and manufacturers. Centres looking to outsource 3D-printed bolus would benefit from clear, open communication with manufacturers and undertake stringent QA examination prior to implementation into the clinical environment.

Introduction

Build-up bolus (BU) is commonly used in radiotherapy to provide dose or tissue compensation during treatment planning and delivery. For the treatment of cutaneous malignancy, BU overcomes the skin-sparing effect of megavoltage photons and electrons which otherwise could cause target under-dosage. Traditionally, tissue-equivalent flexible sheets, hand-made wax moulds, or liquid-saturated cotton gauze wraps were placed directly on skin. These methods can be sub-optimal due to inconsistencies in overall density or due to the manufacturer’s skill level.\(^1\)\(^2\) Variations can also occur if BU needs to be remade multiple times over the treatment course, compounded further when different staff are involved in each recreation. Fused filament fabrication, or 3D-printing, of customised BU can address these traditional BU limitations. 3D-printed BU can conform to the patient's body contours and provide consistent density over the treatment course.\(^1\)\(^2\)\(^3\)
surface, reducing air gaps and improving dosimetry, and can be reproducibly positioned during treatment, while potentially being easier to manufacture. Polylactic acid (PLA), chemical formula \( \text{C}_3\text{H}_4\text{O}_2 \), has been shown to be a widely used material for customised 3D-printed bolus within radiotherapy. It has been shown that when using an infill of 100%, PLA produces a solid bolus with radiological properties similar to tissue. However, variations in chemical formulations can lead to differences in physical properties between nominally “PLA” prints. The addition of coloured dye changing the material’s tensile strength is one example. In addition, print setting variations (such as infill patterns and print speed, temperature, and layer height) can change the distribution of print material and air within the print. These variations can affect beam attenuation and dosimetry for the BU as a whole. If outsourcing the 3D-printing process to external manufacturers, these variations might not be identifiable purely from the finished supplied BU.

This study sourced multiple 3D-printed PLA samples from local manufacturing services to evaluate potential differences in material density and dose attenuation between different nominal PLA prints. The intended use was explained to each manufacturer, and the material (PLA), print size, and uniform 100% infill specified then 3D-printed according to each manufacturer’s processes. We hypothesized that differences in materials and 3D-printing methods can have an impact on BU performance overall, and Radiation Oncology centres considering outsourcing BU printing to external manufacturers must meticulously evaluate this and create appropriate quality checks prior to implementation.

**Methods**

**Sample acquisition and physical density/ Hounsfield (HU) values**

Seven white PLA sample blocks of dimensions 5x5x1 cm, printed at 100% infill, were acquired from three local commercial 3D-printing services, denoted Service A, B and C. All manufacturers had no prior production of radiotherapy services at the time of the study. Services A and C produced two 3D-printed samples each and Service B produced three samples. All services used a MakerBot 3D-printer for sample production. The authors did not participate in the printing process. For each sample, average length, width, and thickness were determined from vernier calliper measurements at multiple positions. Sample weight, from a calibrated scale, was used to determine physical density (g cm\(^{-3}\)).

Samples were CT scanned (GE LightSpeedRT, 120 kVp, 1.25 mm slice width) pressed between 5 cm thick solid water slabs to avoid reconstruction artefacts near sharp corners. Observable internal structure variations were noted, and average Hounsfield unit (HU) values calculated from a volume covering the sample excluding the superficial 1 mm region in all dimensions, to avoid partial voxel resolution blurring with the outside air/slab HU.

**Measurement of the coefficient of equivalent thickness**

Coefficient of equivalent thickness (CET) is a dimensionless correction factor, used in the treatment planning system’s dose calculation to account for radiation dose attenuation through a material. It represents the attenuation through a material of a set thickness, relative to the attenuation that would have occurred through the same thickness of a reference material (typically water). For each sample, a CET value was determined on an Elekta Synergy linear accelerator (linac) for photon and electron beams by comparison against a CIRS Plastic Water slab phantom with known water equivalence (CET = 1).

For photon beams, a small volume ionisation chamber (IBA CC13, with a paired PTW Unidose electrometer) was positioned in Plastic Water slabs at the linac isocentre (100 cm from the linac source) and 5 cm initial build-up (Z) (Fig. 1) for both 6 and 10 MV. Output measurements from a 5 \( \times \) 5 cm field (maintaining full beam transmission through the 3D-printed BU samples) were recorded for various additional Plastic Water slab thicknesses (D) (0.5–1.5 cm). The additional slabs were then removed, and measurements recorded for each BU sample. The BU sample CET could then be calculated as the interpolated Plastic Water thickness that caused the same amount of beam attenuation as the BU sample alone.

For electron beams, measurements were taken with a plane-parallel chamber (PTW Markus). The chamber was positioned with its surface at 100 cm from the linac source and initial build-up of 0.6 and 2.1 cm for 6 MeV. The chamber was positioned with its surface at 102 cm distance and initial build-up of 3.0 and 4.5 cm for 12 MeV.

Output measurements from a 4 cm diameter circular beam were recorded for various additional Plastic Water slab thicknesses (0.6–3.0 cm), covering the typical electron dose fall-off with depth. Measurements for each BU sample were then recorded with Plastic Water slabs at two thicknesses (0.6 and 2.1 cm for 6 MeV, 3.0 and 4.5 cm for 12 MeV) to cover the range of Plastic Water measurements taken. Similarly to photons, the BU sample CET could then be calculated as the interpolated Plastic Water thickness that caused the same amount of beam attenuation as the BU sample.
Treatment planning system (TPS) calculations

To evaluate the dosimetric effect from observed HU and CET variations between prints, test calculations were performed for the two BU samples that covered the measured CET range. CT scans (GE LightSpeedRT, 120 kVp, 2 mm slice width) were taken of each BU sample placed on top of 10 cm Plastic Water. Each scan was imported into a commercial TPS, Elekta Monaco v5.11, and plans generated using Monte Carlo algorithm models on a 2 mm grid spacing, 0.5% statistical uncertainty per beam (photons) or 1x10^6 histories per cm^2 (electrons). Calculations were made first with the BU HU assigned as scanned on CT, then with the BU overridden to match the measured CET, and both compared to calculations with the BU overridden to water (CET = 1). The difference between calculations would then show when the 3D-printed sample could create clinical differences to expected treatments.

Photon calculations were performed for a 5x5 cm field size, 95 cm distance to the top surface of the Plastic Water slabs. Surface doses at the top slab edge (1 mm below BU) and doses at 5 cm depth were evaluated. Electron calculations were performed for a 4 cm diameter circular beam, 100 cm distance to the top Plastic Water slab surface. The R50 depth (the point where dose drops to 50% of the maximum field dose) and R90 (the point where dose equates to 90% of the maximum field dose, commonly used as the clinical prescription depth) were compared.

Results

Physical properties and HU values

Physical properties and HU values of the PLA prints varied across manufacturers and prints (Table 1). While the external dimensions of the samples were close to specification, some showed various degree of warping, i.e., thinner at the edges by up to 1.5 mm compared to the center (Fig. 2). CT scans showed visible internal variations (Fig. 3) including non-uniform print distributions (e.g., B1, B2, C1, C2) and void defects (B3). Physical density varied by 14%, ranging from 1.06 to 1.22 g cm^{-3}. Differences in density were observed between manufacturers (Service C sample densities lower than Service A) as well as between prints from the same manufacturer (Service B). Scanned HU values ranged from -5.1 to 221.0 HU, generally increasing with physical density (Fig. 4) but again showing noticeable variations between manufacturers at nominally similar densities (e.g., B3, 221 HU, versus A1, 140.6 HU, both 1.19 g cm^{-3}).

Coefficient of equivalent thickness (CET) values

Coefficient of equivalent thickness values (Table 1) ranged from 0.95 to 1.17 across the four energies/modalities tested (Figs. 5 and 6). In general, CET values increased with increasing physical density and HU values, with similar variations between manufacturers and prints. CET values were generally consistent between energies, with the largest
variation noted in the Service C prints (which also had the largest HU variations within each print as shown by the standard deviation (SD) values).

**Table 1.** Physical and radiological properties of the 3D printed samples, U = Uncertainty, SD = Standard deviation.

| Service Sample | Thickness (mm) | Density (g cm⁻³) | Hounsfield units (1 SD) | 6 MV U = 0.02 | 10 MV U = 0.02 | 6 MeV U = 0.05 | 12 MeV U = 0.05 |
|----------------|----------------|------------------|------------------------|---------------|---------------|---------------|---------------|
| A1             | 10.1           | 1.19             | 140.6 (11.5)           | 1.11          | 1.14          | 1.14          | 1.15          |
| A2             | 10.0           | 1.22             | 137.8 (14.3)           | 1.12          | 1.13          | 1.16          | 1.17          |
| B1             | 9.95           | 1.09             | 60.9 (25.3)            | 0.96          | 1.02          | 0.96          | 0.95          |
| B2             | 9.95           | 1.13             | 118.4 (41.3)           | 1.07          | 1.05          | 1.03          | 1.03          |
| B3             | 9.90           | 1.19             | 221.0 (12.5)           | 1.12          | 1.17          | 1.14          | 1.15          |
| C1             | 10.0           | 1.06             | −5.1 (58.9)            | 1.04          | 1.09          | 0.95          | 0.96          |
| C2             | 10.0           | 1.08             | −4.0 (52.0)            | 1.05          | 1.09          | 0.96          | 0.95          |
| Mean           | 9.98           | 1.14             | 95.7                   | 1.07          | 1.10          | 1.04          | 1.05          |
| Range          | 0.15           | 0.16             | 226.1                  | 0.17          | 0.15          | 0.21          | 0.21          |
| Coef of Variation (%) | 0.5%          | 5.5%             |                        | 5.5%          | 4.8%          | 9.6%          | 9.6%          |

**Treatment planning system results**

The samples that demonstrated the lowest and highest range across TPS calculations for this sample group were selected for analysis, B1 (CET = 0.95) and B3 (CET = 1.17). Photon surface doses (1 mm below BU) for a 1 cm thick water-equivalent BU were approximately 98.0% for 6 MV (relative to the maximum dose in the beam) and 91.4% for 10 MV. Calculations with the scanned BU samples ranged from −0.3% (B1) to +3.0% (B3) around those expected values. Photon depth doses at 5 cm below BU were all within 1% of the expected water-equivalent BU dose.

Electron R50 depth values in a 1 cm thick water-equivalent BU for this particular field size were approximately 2.56 cm
for 6 MeV and 4.58 cm for 12 MeV. Calculations with the scanned BU samples ranged from $-0.17\,\text{cm}$ (B3) to $+0.04\,\text{cm}$ (B1) around those expected values. R90 depths ranged similarly, from $-0.21\,\text{cm}$ (B3) to $+0.06\,\text{cm}$ (B1).

For all cases, calculations using the scanned HU, and the calculations with the BU overridden to match the measured CET, agreed to within 1% (photons) and 1 mm (electrons), with no trend between the two sets observed.

**Discussion**

3D printing in radiotherapy is becoming more ubiquitous, with PLA commonly referenced for internal (centre-controlled) 3D printing solutions.\textsuperscript{1,2,4–10} However, centres that may not be able to, or choose not to, sanction the cost and ongoing management of an in-house 3D-printer service may look to outsource BU

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**Figure 3.** Radiological variations of all samples. Images taken at most visible point of defect. Window/level adjusted to view density variation.
printing to private or commercial manufacturers. Whilst utilising a radiotherapy-specific manufacturer would be preferred, centres could be limited by other constraints (such as proximity to the manufacturer or shipping time/cost restrictions) that might mean only commercial manufacturers are feasible. The seven samples in this project were commissioned from three commercial manufacturers with 100% infill, a value commonly used.
for radiotherapy purposes. Each manufacturer was informed of the purpose of this study and requirements of the samples however 3D-printing variations were found both between samples and manufacturers. Multiple samples (B1, B3, and C1 visible in Fig. 1) showed obvious visual signs of warping on examination, with print shrinkage noted at the base corners of up to 1.5 mm. Other inconsistencies were only observable after CT imaging (Fig. 2). These included linear low-density variations (A1), higher corner densities (B1, B2, C1, C2), void defects (B3), and apparent density variations with depth (C1, C2). A thicker perimeter, or shell, which is commonly used to increase an object’s strength, may have contributed to Service B and C’s boundary density variation. The shell settings are just one of numerous options available on 3D-printers where small modifications could cause significant variations. Other settings that may affect print quality include, but are not limited to, infill pattern, layer height and width, printing speed, and retraction speed. Other studies concluded variations could be attributed to printing temperature or rate of filament extrusion, a result of the curing process, or the omission of adhesive material on the printing plate. As the authors were blinded to the printing process and all printing details were controlled by the external manufacturers, the reasons behind these internal flaws can only be speculated. These sample variations show that if relying on an external manufacturer for BU prints, clear and open communication on all print settings is essential. A system to confirm printer settings are maintained (or alerting whenever any part of the process changes) would need to be agreed to between the department and the external manufacturer, as they could result in unexpected quality changes.

Measured densities, which varied between 1.06 and 1.22 g cm\(^{-3}\) (Table 1), were consistent with published densities of between 1.12 and 1.25 g cm\(^{-3}\). Both variations between manufacturers (Service A mean = 1.21 g cm\(^{-3}\), versus Service C mean = 1.07 g cm\(^{-3}\)) and variations between prints from the same manufacturer (Service B, 1.09 to 1.19 g cm\(^{-3}\)) were observed.

The CT scanned HU values, in general, increased with increasing physical density, but again variations were observed. For example, samples A1 and B3 had the same density, but the HU values varied by 80.4 units. Comparably, samples B1 and C2 also had a very similar density yet a difference in HU of 64.9 units. Samples from Service C had the largest HU range across the print, likely linked to the observed print and density variations with depth noted earlier.

Measured CET values, in general, increased with HU and density, as expected. The main exception appears to be samples C1 and C2 (average around −5 HU), where the photon CET values were more like B2 (averaging around 100 HU). These samples were also the only ones to show an observable difference between photon and electron CET values. The noted density variations with
depth in these samples cannot be ruled out as contributors to these measured differences.

TPS calculations with samples B1 and B3, which had measured CET values covering the observed range (0.95 to 1.17), showed clinically significant differences for electrons. For a 1 cm thick bolus, the R90 and R50 values were found to shift by up to 2 mm. Clinical bolus thickness in this centre can range from 0.6 cm up to 2.0 to 3.0 cm (for irregular shape compensation such as the ear or nose), so the equivalent shifts could be up to 4 to 6 mm in those cases, potentially resulting in a major dosimetric miss. Routine departmental electron QA practice within our centre is to maintain an electron beam quality (R90 and R50) within 2 mm of their reference values. Adding an additional 2 mm depth variability for every 1 cm of BU material will increase the overall treatment uncertainty significantly. As electron treatments are often used to treat skin lesions within 5 mm of the skin surface, this uncertainty is an area of concern.

For photon calculations, surface dose (1 mm below the BU) varied by up to 3% from expected, while the 5 cm depth dose was equivalent to within 1%. In this case, the depth dose variations are likely to be clinically acceptable after considering standard calculation uncertainties, but surface doses could be an issue, due to the steep dose build-up for photon beams at shallow depths. A concern would be if non-uniform print densities over the BU led to variations in skin dose over the treatment area, especially if using IMRT or VMAT for skin malignancies. Variations in the dimensions of prints (such as not printing an exact match to a DICOM contour shape) could also detract from skin dose uniformity. These variations would not be picked up in a single visual or dosimetric measurement, but might be predicted using CT scans of the printed BU. This would also mean TPS calculations could account for bolus density non-uniformity, at the expense of added planning process complexity.

Other publications have shown similar variations in PLA-printed material, but in general approached printing BU as an in-house solution. For example, one study investigated the HU and density variation of 3D-printed samples using various spools of PLA filament, also reporting a large variation of HU and density amongst samples. The variation was noted to be quite different for different printer types, and the authors recommended thorough quality assurance of printed bolus samples prior to clinical use. Relying on an external manufacturer can make this process more difficult, as a department can monitor consistency in printer settings and material types in ways it cannot do for an external manufacturer. The settings of 3D-printers are essential for producing predictable results, with minor variations creating potentially significant changes. All print settings (not just key manufacturing properties such as 3D printer brand, type, and filament) need to be obtained from the 3D-printing contractor prior to printing, and an agreement on consistency should be defined for all future prints. The department should require the manufacturer inform them if any change in material, printer, print method, or setting occurs.

When ordering from a new manufacturer or after a printer/setting change, it would likely be necessary to rigorously examine every print order, both externally (visually) and internally (via CT scanning) to assess integrity and overall HU values. An alternative method for checking internal integrity is to obtain physical density from its weight divided by the design volume, and compare against an established benchmark reference to within tight tolerances. Our results however show internal density/HU variations can still occur even if the total density is reasonable, due to material distribution differences throughout the print (e.g., shell variations or air/material changes). A CT scan of sufficient resolution should be more reliable for identifying internal variations and can be used to confirm shape accuracy for complex prints (such as those built from DICOM contours on patient CT images). If the quality and HU of externally manufactured prints are established to be stable and reproducible, the inspection process could potentially be simplified (e.g., only CT scanning periodically). However, since a print fault or process change could occur at any time, a compromise could be to maintain CT scanning for any high-risk treatment (plans with strict treatment margins) or complex shape. Re-establishing print reproducibility is recommended after any reported change in printer, PLA filament brand, or service print setting. Similar quality control checks should occur as standard practice following any upgrades (such as for the TPS or CT scanner) in the radiotherapy department. The complexities are of sufficient concern that specialist printing services catering to radiotherapy treatments have been established, albeit typically with an associated cost premium.

While this study aimed to cover a range of potential print quality variations, it remains limited to the small sample size and to the time when the prints were obtained. Despite this limitation, the variations observed can be taken as an example of what might occur if relying on an external manufacturer for printing. Furthermore, whilst the 1 cm thickness is the most common BU thickness used in this department, clinical use would see the BU formed into curved or irregular shapes, and with thicknesses between 0.6 and 2.0 to 3.0 cm. It has been noted that complex bolus shapes with
variable thickness can have lower HU and larger SD variations than a simple 3 cm cube shape. Quality assurance becomes increasingly paramount for these more complex BU, especially for electron treatments. While white PLA was selected for this study based on literature, the number of materials available for 3D-printing continues to increase. Repetition of this work would be warrant for other materials (e.g., flexible PLA or thermoplastic polyurethane).

**Conclusion**

To accurately conform to patient anatomy and provide predictable and reliable treatment dosimetry, 3D-printed bolus needs to be accurate and consistent. 3D-printed PLA bolus from different external manufacturers can show considerable variability in density, HU, and CET, with samples showing clinically significant treatment variations in electron depth dose of up to 2 mm for 1 cm of bolus, and potential uniformity concerns in photon skin doses. Processes verifying both external (visual) and internal (CT scanning) accuracy of these prints is warranted. In addition, ongoing engagement with the external manufacturer and continual quality checks, particularly for complex prints, are recommended to ensure minimal variations between bolus prints.

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**Conflict of interest**

The authors have no conflict of interest to declare.

**Ethics approval**

Ethics approval was not required for this study.

**Data availability statement**

Data within this study is available upon request.

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