Assessing the fit of 3D printed bolus from CT, optical scanner and photogrammetry methods

S. K. Maxwell¹, P. H. Charles²,³, N. Cassim¹, T. Kaim¹,³, S. B. Crowe¹,³

Received: date / Accepted: date

Abstract Bolus plays an important role in the radiation therapy of superficial lesions and the application of 3D printing to its design can improve fit and dosimetry. This study quantitatively compares the fits of boluses designed from different imaging modalities. A head phantom was imaged using three systems: a CT simulator, a 3D optical scanner, and an interchangeable lens camera. Nose boluses were designed and 3D printed from each modality. A 3D printed phantom with air gaps of known thicknesses was used to calibrate mean HU to measure air gaps of unknown thickness and assess the fit of each bolus on the head phantom. The bolus created from the optical scanner data resulted in the best fit, with a mean air gap of 0.16 mm. Smoothing of the CT bolus resulted in a more clinically suitable model, comparable to that from the optical scanner method. The bolus produced from the photogrammetry method resulted in air gaps larger than 1 mm in thickness. The use of optical scanner and photogrammetry models have many advantages over the conventional bolus-from-CT method, however workflow should be refined to ensure accuracy if implemented clinically.

Keywords Radiotherapy, 3D printing, Bolus, Air gap

S. Maxwell
E-mail: skmaxwell94@gmail.com

¹Royal Brisbane and Women's Hospital, Brisbane, QLD, Australia
²Herston Biofabrication Institute, Brisbane, QLD, Australia
³Queensland University of Technology, Brisbane, QLD, Australia


1 Introduction

The use of bolus material is well established in external beam radiotherapy to enhance dose to superficial lesions or to smooth irregular patient contours and produce a uniform dose distribution across a target volume. Bolus is widely used as a surrogate tissue layer, to mitigate the skin-sparing effects of high energy photon beams [1] or shift the dose of electron beams, in order to treat deep seated lesions that extend to the skin's surface or to deliver boost doses to surgical scars while covering underlying surgical beds. The use of 3D printing to fabricate bolus and improve its effectiveness is currently finding its way into clinical practice [2-4].

A common traditional method for bolus is a hand-made wax that can be easily moulded to fit surface contours. Other forms of bolus include wet fabrics, gels or slabs of jelly material [5]. Due to bolus rigidity and variations in patient contour, air gaps can occur between the bolus and skin. Several studies have looked at the clinical and dosimetric implications of the presence of such air gaps [6-13].

The detrimental effects on delivered dose caused by large air gaps (4-50 mm) between bolus and skin during radiotherapy treatments are well known, for both photon and electron beam treatments [6-8]. For example, using 6 MV photon beams with field sizes of 8 × 8 cm² and 5 × 5 cm². Butson et al and Khan et al, showed that 4 mm and 50 mm air gaps could produce skin dose depletions of 4% and 34% respectively [6, 7]. For electron beams, Kong and Holloway have identified surface dose reductions of up to 60% due to air gaps of up to 20 mm [8]. The scale of these differences increases dramatically as field size is reduced, to the extent that several authors have investigated deliberate introduction of air gaps as a means to modify or correct small field dose measurements. Charles et al. [9] investigated the effect of small air gaps on small field dosimetry and found that dose is significantly affected as air gap thickness increases, with a reduction of 11.5% per millimetre for a 6 mm field size.

The above studies indicate a significant dosimetric impact on surface dose can occur with the presence of air gaps for certain treatments. Minimising air gaps between the bolus and surface of a patient through optimising bolus fit can be advantageous for some treatments in providing a uniform, desired dose distribution to the treatment area, and vital for others. The use of 3D printing of patient specific bolus has been investigated to achieve this [2-4, 14-18]. One obvious method for 3D printing bolus requires the patient to undergo an initial CT scan to acquire structures to create the bolus and a second CT scan to ensure the bolus fits sufficiently for treatment [2, 3]. The inconvenience, discomfort, cost and imaging dose associated with repeat CT imaging of radiotherapy patients before and after bolus construction may be avoided by using 3D optical scanning or photogrammetry methods, instead of CT, to acquire the initial images needed for bolus design. Photogrammetry is the use of multiple photographs to ascertain measurements, such as distance between objects. Previous investigations have looked at the application of 3D photogrammetry for the printing of patient specific bolus for orbital tumours [19]. It was found that the method gave a superior fit to that of traditional Superflab bolus, however the cost associated with 3D printing at the time meant the process would only be beneficial for a few small and irregular sites. Photogrammetry has also been used to create a 3D model of a patient’s arm, which was then used to design and print a surface mould applicator for HDR brachytherapy [20]. This was compared to a model created from CT data and a higher accuracy found to be achieved with the photogrammetry model.

Optical scanners use a variety of technologies to capture the images. Structured light is one method, using an LCD projector to project a light pattern onto the object, with the light deformation on the surface recorded by at least two cameras and data points created [20]. Reconstruction results in a polygon mesh of the scanned object, which has been investigated for use in bolus construction [21].

While processes for 3D printing of bolus using different sources of 3D structure information have been investigated separately, a direct comparison of the imaging modalities and the bolus produced from each has not been performed. Furthermore, in previous studies, air gaps occurring between the bolus and patient or phantom surface were usually measured directly on
CT images [4]. This is useful for large, obvious air gaps, however smaller air gaps are sometimes not easily distinguished due to voxel averaging of the CT images. This study therefore uses a more accurate method to quantify small air gaps between bolus and the tissue surface using measurements of mean Hounsfield Unit (HU) values across air gaps, which was recently proposed by Dipasquale et al [22]. In this study, Dipasquale et al’s precise air gap measurement technique was used to assess and compare the fit of nose bolus printed for a phantom using an optical surface scanner, CT and photogrammetry data.

2 Methods

2.1 Imaging Techniques

A CIRS Model 605 radiosurgery head phantom (Computerized Imaging Reference Systems, Norfolk, USA) was used to design uniform thickness nose bolus. The phantom is made of proprietary epoxy materials of tissue equivalence and was imaged using three systems: a 3D scanner, a CT simulator, and an interchangeable lens camera.

2.1.1 Optical Surface Scanner

The metrology-grade Artec Space Spider optical surface scanner provides 3D models with a published resolution of up to 0.1 mm and 3D point accuracy of up to 0.05 mm (Artec 3D, Luxembourg). The 3D model of the CIRS head phantom acquired with this system was exported as a stereolithography (STL) file and the Meshmixer software (Autodesk Inc., USA) used to uniformly expand the model by 1 cm using the extrude tool. The resulting surface image was then cropped around the nose and this shell exported as a new STL, to create the bolus.

2.1.2 CT Scanner

The CT images were acquired with a Somatom Confidence RT Pro (Siemens, Germany) using a head and neck protocol with a 300 mm FOV and a voxel size of 0.6 × 0.6 × 0.5 mm³. Using MIM Maestro ver. 6.7.6 (MIM software Inc, Cleveland, USA) a 1 cm thick bolus was created around the nose, the structure of which was then exported as an STL file, to create the CT bolus. An additional smoothed version of this CT bolus model was created from the CT bolus using the smoothing tool in the Meshmixer software. A smoothing factor of 5 was chosen for this study to best replicate the resolution of the optical scanner.

2.1.3 Photogrammetry

An Olympus OMD E-M10 II (Olympus Corporation, Tokyo, Japan) digital mirrorless interchangeable lens camera, with 16MP and a 14-42mm f/3.5-5.6 kit lens was used to collect photos of the CIRS head phantom; at an approximately even distance of about 50 cm from the phantom, at angles to include all surfaces that were to be recreated. This ended up being 31 photos. Calipers with a ruled scale were included in the images with the head to allow for scaling of the reconstruction. Creation of a 3D model of the head was achieved by uploading these photos into photogrammetry software (3DF Zephyr Free, 3DFLOW, Verona, Italy), which analysed them and chose 26 suitable for reconstruction based on image markers and coordinates it could discern. Once complete, the model was exported as an OBJ file. Meshlab (ISTI – CNR, Italy) was used to scale the model using the callipers with known dimension and a 1 cm thick bolus around the nose then created in Meshmixer, which was then exported as an STL, to create the bolus.

2.2 3D Printing

All bolus were printed with the same slice and print settings on a Raise 3D (Raise 3D Technologies, Irvine, USA) Pro 2 FDM 3D printer, in polyactic acid (PLA, Raise 3D
The head phantom was then CT scanned again with each bolus in place, using the head and neck protocol with voxel size of $0.6 \times 0.6 \times 0.5$ mm$^3$ (120 kV, 48 mAs, 300 mm FOV), to assess the bolus fit. Profiles of the air gap HU values between the CIRS head phantom and bolus were extracted from these images, at 28 points along the phantom/bolus interface using ImageJ (National Institutes of Health, Bethesda, USA).

2.3 Measuring the air gap size between the bolus and phantom

The measurement of small air gap thicknesses is limited by the resolution of the CT images and voxel averaging. The method proposed by Dipasquale et al. [22] accounts for this through calibration of known thicknesses of air gaps using HU values. Dipasquale et al’s method was applied and used to find an average air gap thickness, therefore quantifying the overall fit of each bolus, as follows. CT images were acquired of a calibration phantom, an 11 cm x 1 cm x 1 cm block of PLA containing air gaps with nominal thicknesses of 0.25 mm, 0.5 mm, 0.75 mm and 1 mm. This phantom was designed using Tinkercad (Autodesk Inc., USA) and printed with the Raise 3D Pro 2 printer. These thicknesses were verified with metal feeler gauges. The CT images were acquired with the calibration phantom placed on a slab of plastic water and scanned using a head and neck protocol with voxel size of $0.6 \times 0.6 \times 0.5$ mm$^3$ (120 kV, 48 mAs, 300 mm FOV). Profiles of the air gap HU values were then extracted from these images using ImageJ. The minimum mean HU ± standard deviation was then used to estimate the average thickness of the small air gaps between the 3D printed bolus and phantom. 28 approximately evenly, but randomly distributed points were chosen across the bolus and phantom interface. The air gap at each of these anatomical positions was consistently measured for each bolus. Wilcoxon Signed Rank test was used to compare each fit to that of the optical scanner bolus with p-values < 0.05 considered statistically significant.

3 Results

3.1 Calibration of air gap thicknesses

The mean ± standard deviation of the minimum HU values for each air gap thickness used as calibration, can be found in Table 1 along with the measured physical thickness of the gaps. Figure 1 details a CT slice through the calibration phantom while Figure 2 gives an example HU profile.

| Nominal air gap size (mm) | Physical air gap size (mm) | HU values (Mean ± SD) |
|---------------------------|----------------------------|-----------------------|
| 1.00                      | 0.97 ± 0.1                 | -586 ± 18             |
| 0.75                      | 0.76 ± 0.1                 | -474 ± 20             |
| 0.50                      | 0.51 ± 0.1                 | -325 ± 10             |
| 0.25                      | 0.23 ± 0.05                | -179 ± 16             |
| 0.00                      | 0.00                       | 17 ± 40               |

Table 1 Air gap thicknesses and corresponding HU values

3.2 Bolus fit

The 3D printing of the bolus successfully replicated the anatomical region of interest and planned thickness. The fit of each bolus was assessed by analysing the air gaps in the CT images, and upon visual inspection, the optical scanner bolus appeared to give a noticeably superior fit. The inner and outer surface of the bolus contoured from the CT data was not as smooth as the other three bolus, as a result of CT voxelisation. A CT image of the fit of each bolus is shown in Figure 3.
The mean air gap thickness between the phantom and the bolus (± standard deviation) for the bolus created using optically scanned image was 0.16 mm (± 0.21), for the CT data bolus it was 0.47 mm (± 0.29), the smoothed CT bolus was 0.23 mm (± 0.24). 46 % of the photogrammetry bolus points measured had air gaps larger than the calibration range (0-1 mm). The mean size of the air gap in the remaining points was 0.47 mm (± 0.28). This clearly did not fit as well as the other bolus. An example air gap HU profile is shown in figure 4.
As the optical scanner has metrology-grade resolution and gave the best overall fit, it was considered the “gold standard” in this study. Statistical analysis was performed comparing the air gap thicknesses to those of the bolus created using the optical scanner images and found that there was a significant statistical difference between this and both CT and photogrammetry models (p-value << 0.001 for both comparisons), however only a small statistical difference exists between the optical scanner and smoothed CT bolus (p-value < 0.04).
4 Discussion

Bolus for a head phantom were successfully 3D printed from optical surface scanner data, CT data and photogrammetry images and the fit of these bolus on the phantom then assessed. The method proposed by Dipasquale et al. [22] was implemented to use the HU values of small air gaps from CT images to quantify the overall fit through looking at the mean air gap thickness. It was found that the bolus contoured from optical scanner data gave a superior fit, with a mean air gap thickness of 0.16 mm. This is expected as the scanner has metrology-grade resolution and agrees with findings in the literature [22] The fit of bolus created using CT data is affected by the resolution of the initial CT scans and is significantly improved with post-processing smoothing, with the result of the smoothed CT bolus being comparable to that of the optical surface scanner. The use of smoothing could be easily implemented into the current bolus-from-CT workflow in departments without access to, or established workflow for an optical scanner, while achieving a superior fit to traditional bolus forms and improving dosimetry by minimising air gaps present in the raw CT data. The fit of the photogrammetry model contains many air gaps larger than 1 mm in thickness. While previous investigations have found photogrammetry to produce a bolus of superior fit compared to conventional CT-based 3D printed bolus [19, 21], the bolus resulting from photogrammetry in this study gave a poorer one. Possible reasons for this include scaling uncertainty and possible geometric deformities arising from the post processing methods. While having many of the same advantages as an optical scanner workflow, as well as being potentially cheaper and more accessible, a system without the use of structured light has limitations in accuracy and resolution.

The use of optical surface scanner data to contour bolus has been shown to be a superior method to using CT or photogrammetry data in terms of fit, as well as reducing the number of scans a patient undergoes, minimising dose received. The scanner has a high, metrology grade resolution and gave little to no artefacts in the structure image. Clinical use of this method, as well as photogrammetry, over conventional CT imaging would also mean the patient is free and more comfortable, without the need to be confined to a CT couch. The scanning or

Figure 4 Example HU profile across the air gap between the head phantom and each bolus, at the same anatomical location
photography of a patient is time efficient, with required images being obtained within a matter of minutes. This could be completed easily within the already established scan appointment time, possibly reducing times and improving departmental workflow. The printing of bolus prior to CT simulation also gives the advantage of accurate bolus density and homogeneity modelling in planning. However, this workflow would mean no initial CT data set is available before the bolus is created.

This study involved a number of limitations. Firstly, the measurements were performed on a head phantom rather than a real patient. While the phantom is made of tissue equivalent epoxy material, it is solid and lacks the compressibility and deformability of a real patient. A real patients’ contours could change between bolus creation and treatment and these potential variations are not represented here. Investigations into the use of flexible 3D printing materials could minimise variations in the future. One limitation of the Dipasquale et al. method is that the calibration and measurement conditions differ, as the calibration HU voxel value relates to the attenuation properties of air and PLA material, while in the measurements the CIRS phantom is also a factor. As both these materials are approximately tissue equivalent, the effect of this would be small. Inherent limitations with the use of an optical scanner or camera for photogrammetry exist in their ability to scan concave surfaces and cavities. With sufficient lighting or even potentially the use of markers on the target during scanning, as well as adequate training, the risk of missing areas while scanning can be minimised. This work was only performed with a single model of optical scanner and a single camera. The higher the resolution of these devices, and the better the acquisition, the more accurate the resulting model will be. While metrology grade scanners will give the most detail, this level of resolution is not necessary. Any device with a resolution better than that of the CT scanner will achieve better models. The use of small point and shoot cameras for photogrammetry could achieve suitable models with further investigation into accurate scaling and post processing.

While large air gaps between bolus and a patient’s surface can affect the planned dose distribution, the literature suggests that air gaps in the order of a few millimetres thick have no significant affect for large megavoltage photon fields [6]. The optical scanner bolus, CT bolus and smoothed CT bolus are therefore all clinically suitable for this application. However, the presence of small air gaps in bolus fit could significantly impact the dose distribution for very small field treatments [9] or highly modulated fields. Departments should take into account the types of treatments the bolus is to be used for, before establishing tolerances for acceptable air gap thickness. The achievable fit of any bolus, including 3D printed bolus, is inevitably affected by patient factors such as variation or deformability in the skin or soft tissue, therefore any accuracy in bolus fit exceeding this is excessive. The methods described in this paper can be easily applied by other departments to assess the fit and clinical suitability of bolus produced from these and other imaging modalities.

5 Conclusion

The methods of using optical scanner, CT and photogrammetry imaging to produce 3D printed bolus were assessed and the fit of the resulting bolus compared. The bolus produced from the optical scanner method was found to have the best overall fit, with a mean air gap HU value corresponding to a thickness of less than 0.25 mm. An optical OS bolus workflow also has the advantage of ease of use and eliminates the need for two CT scans, reducing the radiation dose the patient will receive. The bolus produced using the CT data was still clinically suitable, with the fit improved by smoothing. The bolus produced from the photogrammetry method contained air gaps larger than 1 mm in thickness. With further improvement of the workflow, photogrammetry could be a more accessible alternative to optical scanning for radiotherapy departments and produce a bolus accurate enough for clinical use while also improving patient planning experience and reducing the imaging dose they receive. The methods used in this investigation are useful to departments, as clinical suitability of 3D printed bolus should be assessed dependent upon the types of treatment they are to be used for.
Acknowledgements  This work was supported by a MNHHS-funded Herston Biofabrication Institute program grant.

Conflict of interest
The authors declare that they have no conflict of interest.

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