Exploring properties of 3D-Printed Bolus: Optimal choices for radiation therapy

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Background The use of 3D-printed boluses in radiation therapy has gained significant attention due to their potential to improve treatment accuracy and patient comfort. However, comprehensive validation of these boluses using multiple validation methods and statistical analysis is crucial to ensure their effectiveness. This study aims to characterize potential candidates to be used as 3D-printed bolus via CT scans, PDD scans, and dose measurements

Methods CT scans were performed to evaluate the radiographic properties of 3D-printed boluses, made of Premium PLA, Standard PLA, ABS, Polycarbonate, ASA or PET-G. As a standard, a gel type, commercially available bolus was used. The mean Hounsfield Unit (HU) profiles of the 3D-printed materials were compared to the commercial bolus using Eclipse Treatment Planning System (TPS) unit. Additionally, PDD scans and absolute dose measurements were performed to evaluate the performance of the 3D-printed samples in delivering the desired surface dosage and to analyze how these materials behave under irradiation. Dose measurements were recorded for each material, as a second validation method, with the commonly used commercial bolus and a solid water slab serving as reference in the dosimetry process. The objective of the third calculation was to evaluate the concurrence between the measured and calculated doses from a dosimetric standpoint. All datasets were extracted from TPS generated plans to determine if the area under the dose curve for the build-up region of each 3D bolus held substantial significance for this study. Concordance correlation coefficient analysis, a measure of agreement between two variables, was performed to measure the agreement between 3D materials and the commercial bolus in terms of suitability to be used as clinical device

Results CT scans revealed that the 3D-printed materials exhibited comparable attenuation properties to the commercial bolus (- 39.4 HU). The mean CT HU profiles of the 3D-printed materials were as follows: ABS (-144.53 HU), ASA (-124.40 HU), Premium PLA (9.55 HU), Polycarbonate (-140.79 HU), Standard PLA (-68.58 HU), and PET-G (-113.159 HU). The mean CT HU value for Premium PLA (9.55 HU) was significantly different from the mean CT HU values of the other materials. Compared to ABS, ASA, Polycarbonate, Standard PLA, and PET-G, the Premium PLA material had a much higher HU value. This suggests that Premium PLA has a higher radiopacity or density compared to the other materials. PDD scans demonstrated that the presence of air gaps between the bolus and the surface resulted in a displacement in the depth at which the maximum dose surface was achieved. Commercial Bolus had a surface dose of Ds = 96.32%, Standard PLA Ds = 92.36%, Premium PLA Ds = 92.75%, ABS Ds = 91.54%, PC Ds = 90.41%, ASA Ds = 89.07%, and PET-G Ds = 92.29%, respectively. When an air-gap of 0.5 cm was introduced, the values decreased uniformly with around 1% for each material, whereas for a 1 cm and for 1.5 cm air-gap, the values decreased further with around 2% for each distance resulting values still around 90%. The measurements indicated that two materials (e.g. ASA and PC), exhibited higher sensitivity to irradiation, rendering them inefficient for increasing the dose in the build-up region. Analyzing the dose profiles (%) as a function of the distance (cm) drawn for each individual material, almost perfect agreement was found ($\rho c > 0.99$) between Bolus - Solid Water (clinical references), Bolus - Standard PLA ($\rho c = 0.9987$), Bolus - Premium PLA ($\rho c = 0.9995$), Bolus - ASA ($\rho c = 0.9963$) Bolus - PET-G ($\rho c = 0.9984$), whereas between Bolus - PC ($\rho c = 0.9499$) and Bolus - ABS ($\rho c = 0.937$) a moderate agreement was observed. From a statistical perspective, the concordance correlation coefficient analysis unveiled that the ABS material, demonstrated an unsuitable classification for this investigation. Thus, out of the six materials tested, 3 turned out to be suitable as candidates for 3D- printed bolus (e.g. Premium PLA, Standard PLA and PET-G)

Conclusion Our study found that 3D-printed boluses are effective for delivering surface dosage, prepared from materials comparable to commercially available options. Based on the above presented results, our study identified Premium PLA, Standard PLA and PET-G as materials for 3D-printed bolus with statistically significant improvement in dose delivery.These findings emphasize the potential of 3D-printed boluses in optimizing radiation therapy outcomes.

Keywords 3D bolus, dose distribution, printing materials, radiotherapy

Evaluation of skin dose in post-mastectomy irradiated patients using an individual bolus made using 3D printing with a controlled air gap.

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Background. Skin reactions following breast cancer radiotherapy occur in 80-90% of patients as a direct result of treatment. Numerous studies have demonstrated a correlation between increased risk of moist desquamation and the specific kinds of bolus material. Additionally, there is also a matter of the frequent occurrence of air gaps that poses a significant challenge. Recommendations regarding bolus thickness vary based on geographic location, type of breast reconstruction, radiotherapy plan, and individual physician practice. Despite the above-mentioned challenges, there is substantial evidence supporting the necessity of bolus application for post-mastectomy patients. To address limitations associated with commercially available bolus, 3D-printed personalized boluses have gained popularity. The ability to precisely replicate the chest's surface minimizes inaccuracies in tissue-material contact. However, directly applying such boluses to the patient's chest may still result in adverse skin effects. An experiment was designed with a 3D-printed bolus positioned 1cm away from the skin. This approach reduces the risk of acute skin reactions, although it is not a standard procedure and requires thorough follow-up evaluation.

Methods. The main thrust of the research was the preparation of personalized, 3D-printed boluses. The next step was making a personalized phantom representing the chest wall of a patient who had previously undergone breast removal surgery. Based on current publications it was agreed to test two boluses with varying infill levels: 10% and 40%. The thickness of both printed boluses was maintained at 1 cm. The material used for all 3D prints was PLA. The specially designed holder was mounted on the therapy table. To verify the assumptions of the project, dosimetric measurements were made using radiochromic films placed at 5 different locations on the phantom. Irradiation of the phantom was carried out using a 6 MV linear accelerator and VMAT technique. Reproducibility analysis of bolus placement was also performed.

Results. It was observed that only when measured without the bolus are the doses, from the Treatment Planning System, significantly higher than those recorded on radiochromic films. In all other cases, the trend is the opposite, but the differences between the numeric results are much smaller oscillating from 1.1% to as much as 8.2%. Regardless of the type of measurement, the highest doses occur in the case of using the gel bolus, which is the ongoing standard for clinical use. To quantify the differences occurring between the doses measured in different cases, their percentage comparison was carried out.

Discussion. One of the biggest problems during the testing process proved to be the holder, which was supposed to hold the bolus over the surface of the phantom. Unfortunately, limitations including therapy table design and the geometry of the holder prevented reproducible bolus placements. Despite the difficulty in positioning the mount, from the results of the reproducibility of bolus placements over the surface of the phantom, it was established that the doses on the surface were not significantly affected. In addition, TPS is not adapted to calculate the parameters of the therapeutic beam for areas containing large air gaps. This may have caused the differences between the doses from the TPS and those measured with radiochromic films that are ranging from a few to several percent. More time would need to be spent on implementing a new solution to enable such calculations, but this is a topic to be addressed in another extensive research work. A surprising result obtained by this study was a significant difference in the doses recorded on the overlaid radiochromic films. It can be deduced that a soft electron spectrum appeared during the measurements, which changed significantly over the thickness of the films. The total thickness of the two overlaid film strips does not exceed half a millimeter.

Conclusion. In conclusion, trends toward personalization of treatment in radiotherapy have been observed. The use of 3D printing allows the creation of accessories perfectly tailored to an individual patient, based on medical images, fits into this trend. Due to the extensive doubts and technical problems of using 3D-printed boluses offset from the skin surface, it would be advisable to consider using them directly on the patient's skin, however, with some new assumptions.

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Printing Shielding and Bolus for Electron Radiotherapy for Skin Cancer

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Keywords: radiotherapy, electron shielding, bolus, treatment techniques, 3D printing

Background: Electron beam radiotherapy is used to treat skin cancers, including squamous-cell and basal-cell carcinomas. At The Royal Marsden, Sutton, we treat approximately 65 electron patients annually. The electron beam is produced by a linear accelerator and due to the scattering properties of the beam the field needs to be shaped by shielding structures on or close to the patient's surface. It is possible to create a custom-shaped endframe, but shielding on the patient's skin is preferable because of reduced penumbra and improved localisation. Bolus may also be required to modify the dose distribution of the electron beam in tissue. Common practice across the UK is to produce a plaster cast of the patient prior to treatment. Shielding is then created manually by hammering layers of lead on the plaster mould. Bolus can be created by pouring and moulding wax. These are time-consuming and labour-intensive processes.

Aim: To setup a clinical workflow for using the Objet Eden 350 3D printer (Stratasys) to create shielding and bolus for patients receiving electron radiotherapy. 3D printing of structures based on the patient's CT scan facilitates a stream-lined process to create patient-customised shielding.

Method: An MDT was set up to investigate each aspect of the process. CT scans of phantoms were imported into the Raystation Treatment Planning System (TPS). Templates and scripts were set up to streamline creation of shielding and bolus structures. These are then exported via STP files to Inventor software and printed on the 3D printer in MED610 biocompatible plastic. To eliminate air pockets in the Cerrobend the MED610 printed mask is placed in a sand mould and the molten metal is poured into the mask under temperature-controlled conditions. Other testing included: transmission measurements of MED610 for bolus suitability, profile measurements in a water phantom under test shields, checking and manufacturing tasks to be completed by staff, and end-to-end testing of the new process. Once the process was designed, clinical workflow management and documentation was produced using Elekta SmartClinic.

Figure 1: Creation of the mask in the TPS (Raystation), printed MED610 mask and Cerrobend- filled mask.

Results: The transmission of MED610 was 0.95 times that of water. The profile under the shielding containing Cerrobend shows negligible transmission and a sharp penumbra. MV imaging showed no air pockets in the Cerrobend on printed prototypes.

Conclusion: Testing completed so far has shown that the printed materials are fit for purpose, and the workflow is feasible in clinical timescales. We aim to complete testing and start using the technique clinically this spring. In the longer term, it will be possible using this technique to model the electron dose distribution and so produce computer-planned treatments with surface shielding.

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3D Printing Bolus For Use Over and Under Head Shells In Head And Neck Planning

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Background:

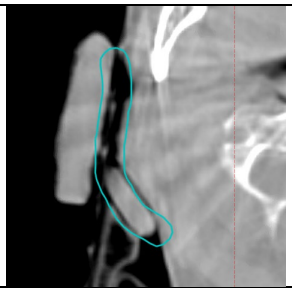
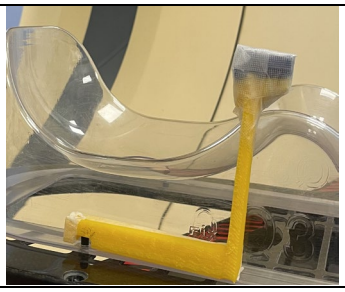
Bolus is used for roughly 50% of VMAT Head and Neck plans at North Middlesex Hospital. Patients are scanned without bolus allowing the clinician to decide where to apply the bolus on the planning CT. Reference set up fields are then created which can be projected onto the head shell to mark on the bolus position, and custom bolus made to fit using a Wax/Vaseline mixture (Waxeline). This material is malleable but doesn't always hold its shape and may not conform perfectly to the patient's surface / head shell. The clinician drawn bolus will often be in a region where it should ideally lie under the shell. Previous solutions to this were to leave the bolus on the shell (and accept part of the delivered Arcs would be lacking in bolus for part of the beam delivery and have a potentially large gap between bolus and skin in this region), or alternatively to cut a hole in the shell (which is not ideal) so the bolus can be better conformed to the patient's skin.

Methods:

To overcome these shortcomings, we have developed a system of 3D printing 'support' structures that hold the bolus in place under the head shell, and more recently printing the bolus itself. Support structures are printed using the lowest density setting with the minimum amount of material to minimise the impact on dosimetry. The base of the support runs along the base of the headrest with a notch to fit over the locator pin in the headrest for indexing. The bolus itself may be made from Waxeline or 3D printed bolus. Waxeline bolus is made by moulding to a 3D printed skin surface template. Bolus and supports are printed on a RAISE3D Pro2 3D printer using PolyLite PLA Filament.

Results:

3D printed bolus has been fine-tuned and tested for dosimetric equivalence to water. Less than 0.5% dose difference has been measured in the build-up region when comparing with solid water at a depth of 1cm. The dosimetric impact of the support structures has been evaluated, and with an attenuation rate of < 1% per cm, considered to be negligible in the context of a very small sector of a VMAT plan arc. CBCT images show an accurate positioning of bolus is achieved.

Image 1. CBCT showing 3D printed bolus both inside and outside head shell plus support and clinician's bolus structure.		Image 2. 3D Printed bolus (blue) attached to support (yellow) indexed to locator pin on headrest.	

Discussion:

3D printing bolus and supports shows a definite improvement in the conformance of bolus to the patient's skin. Currently it can be a labour-intensive process to generate the VOI structures required but set up for the treatment radiographers is relatively quick and easy. Care is required when creating VOIs to ensure there are no sharp corners that might risk causing injury to the patient.

Conclusion:

3D printed bolus and support structures can improve bolus conformance and hence the dosimetry of delivered plans. Streamlining of the process is required to optimise the planning workflow.

Key Words: 3D Printing, RAISE3D Pro2, PolyLite PLA Filament, Bolus, Head Shell, VMAT

Investigating the feasibility and dosimetry of 3D-printed bolus in electron radiotherapy

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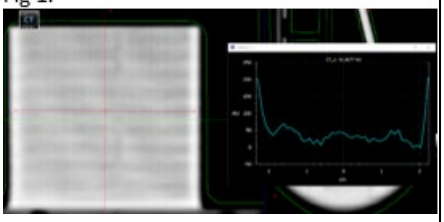
Background.

Electron radiotherapy uses bolus to augment the dose to the skin surface[1]. Wax is often used but only a certain level of precision can be achieved resulting in air gaps between the patient surface and the bolus, reducing skin dose[2]. 3D printers can print complex shapes with high resolution[5] allowing for higher precision bolus[3]. 3D-printed bolus is more comparable to planned bolus allowing for more accurate dose calculations[4].This work investigated the properties, dosimetry and feasibility of using 3D-printed bolus.

Methods

Four 5x5x5cm cubes were printed in PLA and CT scanned. A body phantom was CT-scanned and electron plans created in Eclipse. The data was exported to Adaptiiv's 3D bolus software to create a digital bolus model. Wax and 3D-printed boluses were produced. The treatment plans were delivered to the phantom twice, once with wax bolus and once with 3D-printed bolus. TLDs were used to measure the dose. To investigate the effect of CT slice thickness the body phantom was scanned at 1mm slices. An identical plan to one for the 3mm scan was created.

Fig 1.



Results

The mean HU for the PLA cubes was 71.5. The printing process results in higher density at the perimeter of the print (around 200 HU) and multiple point dose calculations suggest that the HU through the main body of the prints was closer to 50 (Fig 1.).

The difference between expected and measured dose was lower for the 3D-printed bolus (Table 1).

Table 1

Plan	Bolus	Dose per fraction (Gy)		Difference (%)
		Expected	Measured	
Plan_PTV1	Wax bolus	4.36	4.23	-3
	3D-printed bolus	4.51	4.41	-2.2
Plan_PTV2	Wax bolus	4.46	4.38	-1.81
	3D-printed bolus	4.53	4.5	-0.66

The expected dose to the TLD reference point for the plan created from the 3mm slice scan in comparison to the 1mm slice scan was 42.01 Gy (93.35%) and 42.29 Gy (93.97%) respectively.

Discussion

The mean HU for PLA (71.5) is significantly closer to water (0) than wax bolus (-150), suggesting that PLA may produce a bolus of closer tissue equivalence than wax. The effects of the high density perimeter on scatter must be investigated. Bolus is much thinner than 5cm (usually 0.8-1.4 cm) so the high density perimeter will be a larger proportion of the print. The TLD results indicate that 3D-printed bolus can result in dose more similar to the dose calculated by the treatment planning system. This could lead to tighter dose tolerances and more accurate treatment. A small increase in percentage of dose delivered to the reference point of 0.6% was found for the plan created on the 1mm slice scan. Our current in-vivo dose information indicates delivered dose is within 0.5% of expected so the benefits of the 1mm scan may be negligible**Conclusion.** Conclusion relating to the aim of the study.

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REVOLUTIONISING LEAD MASK PRODUCTION FOR SKIN CANCER PATIENTS: LEVERAGING 3D SCANNING AND PRINTING TECHNOLOGY

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Skin cancer treatment often necessitates the use of lead masks to shield health tissue during radiation therapy. Traditionally, the production process involves the creation of plaster casts, produced using an alginate impression, the production of which can be uncomfortable and time-consuming for patients.

This study explores the use of 3D scanning technology in the medical field and specifically its role in removing the need for the production of plaster cast moulds for patients with facial skin cancer. By examining the advantages, such as time efficiency and patient comfort, we are aiming to streamline the process as much as possible while maintaining or improving the quality of the masks produced.

The new process requires the production of a scan of the treatment area using the handheld 3D scanner which is then converted in to a 3D printable file and uploaded to a 3D printer. When the print is complete the lead mask can be made using the 3D print as a template.

Our results after using this new procedure have shown an improvement in the patient experience, a reduction in appointment times and staff time required per patient as well as potential cost savings on materials.

Potential issues with this new approach have proven to be some issues with how the wire outline is formed on the print and how that can interfere with mask production as well as the cost to implement this system due to the one-off purchase of expensive equipment.

In conclusion we believe this new method is advantageous for patients and staff and the use of 3D scanning could lead to multiple other uses within the NHS.

New Method

The new method currently requires a member of physics to bring the laptop and 3D scanner down to the mould room and set up. The patient is then set up on the couch and marked with a pen as before. At this point a thick wire is attached to the inside of the marked area (this will create a raised line around the treatment site that the engineers will use as an indication of where to cut the lead. The 3D scanner is then held over the patient and moved around until a full scan of the patient's face has been achieved. The scan can be cropped down to just the treatment area and areas of interest nearby (for the production of the mask we prioritise the bridge of the nose as this is used to anchor the mask when on the patient). The cropped scan is then saved as an stl file and moved to the 3D printing software. The scan is then loaded to the printer and the printing starts. On average the prints take between 6-12 hours to complete. Once complete the print can be handed over to the engineers to make the mask.

Advantages

This whole process can be completed in as little as 10 minutes.

There are many advantages to the new method over the old. The benefits to the patient are obvious, shorter appointment times and no need to cover the patient in alginate to create a mould for plaster. The benefits to staff are less training as training on the 3D scanner is far easier than training to make an alginate mould. With shorter appointment times means less staff time commitment as from setup to printing can take as little as 30 minutes. There is also little waste created by this process. The cost per patient is much lower as even the larger prints only cost a few pounds in printer filament.

Disadvantages

The most obvious issue for any department interested in employing a similar method for mask production is the up front cost. The scanner cost £2000. The scanner software also requires a high-end gaming laptop or equivalent computer in order to run effectively. These can cost in the region of £1500. Of course a filament 3D printer is also required. The departments cost £4000 but a cheaper one would work assuming it had a large enough print bed.

We have little data with respect to patients with darker skin tones and how the 3D scanner manages.

The other issues revolve around the production of the mask. We have found that when using the wire around the tip of the nose this produces a mushroom shape that the lead can get stuck under.

From Patient to Print in 10 years: Shells, Moulds and Bolus

John Mills, Print Easy Acrylic Shells

Key words: 3D printed bolus, radiotherapy, mouldroom devices

Background

In 2013, cheap desktop 3D printers with limited volume were readily available. By 2014 an affordable acrylonitrile butadiene styrene(ABS) printer with the print volume of a human head provided a real opportunity to explore the potential for 3D printing in radiotherapy. There is a significant gap between the patients treatment requirement and being able to print a shell, mould or bolus. This presentation will describe all the stages, aspects, limitations and experience of deriving the patient data from CT and surface scans, transforming this data into printable files and printing them.

Methods

At the onset of this project it was clearly apparent that there were three major hurdles to overcome in bridging the gap between patient and print.

1. The topography of the patient needed to be acquired.
2. A means to process this information into a required object which could be printed was required.
3. The object had to be reliably printed.

Each of these requirements represented a learning challenge to identify the means and develop the skills and knowledge to achieve them. A significant requirement at all time was to make the process affordable.

In addition, most radiotherapy centres treat in different ways and use different mouldroom devices. So there could be no 3D printed device which would be of universal interest. However, being able to bridge the gap for one device would develop skills and expertise and it would demonstrate that in principle the gap could be bridged.

The first and simplest goal was to print a facial shell. While it is something no longer universally required it is a recognisable device upon which other techniques and devices could potentially be developed. An electron treatment technique with which the author was familiar, involving a mask and an applicator alignment device was translated into a 3D printing process. Following this, scans of plaster moulds to provide moulds for wax build up developed and extended skills and knowledge. Bolus prints were investigated in ABS and Polylactic acid (PLA) filament and resin printing. Moulds to make plaster casts were developed to eliminate the need for alginate impressions. Embedding HDR source catheter guides into shells to reproduce Paris system style treatments was developed. Phantoms and bespoke attachments to electron applicators for dose measurements were produced and used for dose verification measurements. The use of 3D printed moulds for low melting point (LMP)alloy masks extended skills and expertise as well as enabling the production of such devices.

Results

With regard to the three major aspects the following has been achieved over the ten years.

1.Topography. Surface scanning was investigated to determine its limitations, resulting in a patient scanning technique. Accuracy of performance, quality control and comparisons were made with scanners. Derivation of bolus from the DICOM-RT file was achieved using CT-Slicer.

2. Processing. A commercial platform, nettfab was identified as an essential element in this aspect. All the development was done on this platform although one free platform, MeshMixer was then used to reproduce the processing for a plaster mould. A free and easy to use CAD package was extensively used to produce devices and fittings which were embedded into the print file.

3. Printing and printers. Based upon initial advice from a supportive 3D printing bureaux, expertise, knowledge and skill was built up on achieving reliable prints, identifying print limitations and problems and modifying designs appropriately to reliably obtain good quality prints.

Discussion

Integrating 3D printing into radiotherapy requires several things which can be achieved by or in part by dosimetrists, radiographers, technicians and scientists. There is a substantial learning curve but it requires modest resource and staff commitment.

Conclusion
The work undertaken over ten years has demonstrated that the skills for 3D printing can be acquired, that there are tools available to enable 3D printing for radiotherapy to happen. And that with a proactive approach it now has an established role.

Embedding Dosimeters in 3D Printed Bolus

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Key words: 3D printed bolus, radiotherapy, radiation dosimetry, invivo dosimetry

Aims and Background. Three dimensional printing with flexible resin can now be used to produce intricate bolus which may reduce the time for patient set-up and ensure a reproducible dose distribution (1). The aim of this work was to assess the water equivalence and the fit of a printed bolus to the surface of a phantom. Then to devise a method to place small solid state dosimeters into the printed bolus in order to make in-vivo measurements.

Methods. The water equivalence of bolus, printed on a FormLabs (Massachsetts) Form 3+ printer using their 50A resin, was measured for 6 and 10 MV photons as well as for 6, 9 and 16 MeV electron beams using the displacement of depth dose curves using 10 mm and 20 mm flat bolus. Another three slabs of bolus, chosen to be nominally 5 mm thick, were printed for the irradiation of a head and neck phantom. Two were derived from a treatment planning system and one derived from a surface scan of the phantom. The conformity of the bolus fit to the phantom, and uniformity of bolus thickness, was assessed using CT scans of the phantom with the boluses in place. The dosimeter cavity design and techniques to embed them into the bolus was devised for netfabb software. Finally, a chosen bolus was reprinted with cavities placed in a field assessment pattern enabling solid state dosimeters (strings of micro-silica bead TLDs, TrueInvivo) to be fitted.

Results. For 6 and 10 MV photons, the difference of water to 10 mm of bolus was less than 0.5 mm while for the electron beams the difference ranged from 1.2 mm to 0.6 mm for 10 mm and 20 mm of bolus.
The surface scanned bolus mean thickness was 4.7 ±0.2 mm compared with the manually outlined mean thickness of 3.4 ±0.9 mm and the automatic outlined thickness of 3.9 ±0.4 mm.
The conformity of fit was assessed by measurement of the gap between the bolus and the phantom surface. This mean gap ranged between 1.4 ±0.4 mm to 1.75 ±0.7 mm depending upon which bolus was considered.
There was a significant difference between the mean gap for the surface scan bolus and the mean gap for the manually outlined bolus. However the mean gap measured for the automatic outlined bolus was not found to be different from that of the surface scan or the manually outlined bolus.
The resulting bolus print readily accepted the dosimeters and held them securely, providing a bolus capable of undertaking in-vivo dose measurements once the shielding effect of the dosimeters in the bolus is established.

Discussion. The results indicate that bolus can be printed in an almost water equivalent resin which fits well to a surface irrespective of the print file being derived in a treatment planning system or from a surface scan. The surface scan bolus provides the most uniformly accurate thickness. The processing of the bolus to embed dosimeters was found to require skilled knowledge and operation of the processing software as well as simple cavity design.

Conclusion. 3D printed bolus can be designed to have cavities into which solid state dosimeters can be loaded to provide in-vivo dose measurements. Strings of Micro silica bead TLDs were found to be an easy and practical choice of dosimeters to work with.

Reference 1: Evaluation of 3D printed bolus for radiotherapy using megavoltage X-ray beams. C Zhang, W Lewin, A Cullen, D Thommen and R Hill. Rad Physics and Technology (2023). 16:414-421.
https://doi.org/10.1007/s12194-023-00727-0

Tissue-equivalence of 3D-printable thermoplastics in photon and proton therapy

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Background: 3D-printing is an attractive solution in the manufacturing of physical phantoms for QA in radiotherapy [1], [2], [3]. We compared the mass density and radiological properties of 3D-printable thermoplastics against biological tissues in photon and proton beams [4], [5].

Methods: 10x10 cm^2 slabs of varying thickness were 3D-printed (Raise3D Pro2) with six thermoplastic materials: PLA, ABS, PETG, PMMA, HIPS and StoneFil. Mass density (ρ) was calculated for these materials from measured volume and mass (Duratool digital calliper; Bel Engineering scale MW723i-M). Hounsfield Units (HUs) were derived from CT-scans acquired with two scanners (AnyScan TRIO® SPECT/CT and Philips Spectral CT 7500) operating at 120kVp. Experimental relative electron density (RED) and relative stopping power (RSP) values were obtained through measurements in a 210 MeV proton pencil-beam (ProBeam, Varian Medical Systems; Giraffe detector, Ion Beam Applications S.A.) and in a 6 MV photon beam (VersaHD, Elekta; Semiflex3D 31021 ionisation chamber, PTW Dosimetry). Then, the ρ, RED, RSP and HU values of the thermoplastics were compared against those of biological tissues. The ρ and HUs of fourteen soft and bone tissues (from adults and children) were retrieved from published studies [4], [5] while RED and RSP were calculated mathematically from their elemental composition [4].

Results: Figure 1 shows the ρ, RED, RSP and HU values for the biological tissues and thermoplastics. Stonefil showed properties closer to the ones of cortical bone, especially for a 5-year-old child, with differences of 10.74%, 21.80% and 10.72% for ρ, RED and RSP, respectively, and comparable HUs. The properties of PLA, ABS, PETG, PMMA and HIPS were closer to soft tissues. ABS closely matched adult and child adipose tissues, with percentage differences of {0.42,0.93}%, {1.68,2.90}% and {1.24,1.94}% for ρ, RED, and RSP, respectively, and similar HUs.

Discussion: The materials considered in this study have good potential to act as tissue substitutes in radiotherapy. StoneFil was the best candidate for a bone equivalent material due its higher density value. ABS was a good substitute for adipose tissue, with percentage differences below 3% for all properties. PMMA, PETG and PLA were good candidates to substitute skeletal muscle, brain and lung tissues. No thermoplastic had comparable HUs to lung.

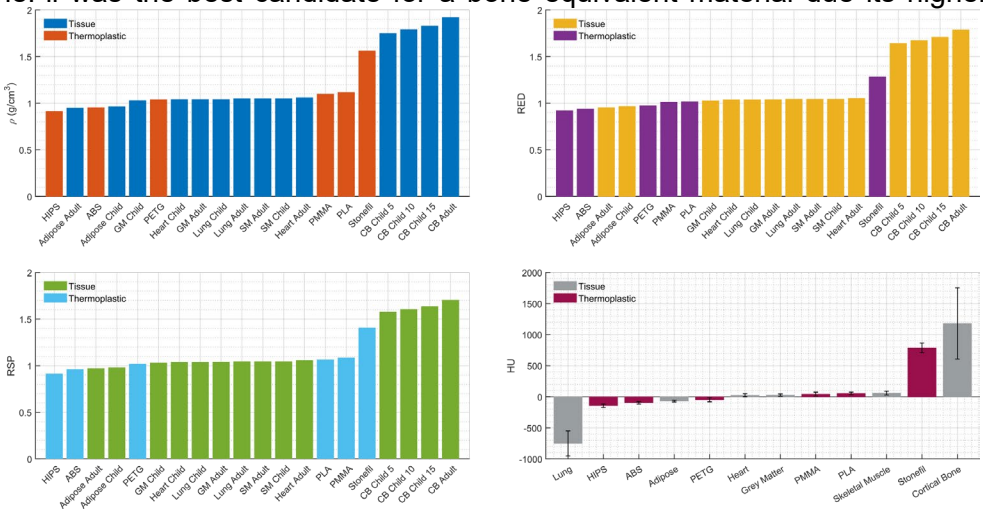

Figure 1: Waterfall plots of experimental (thermoplastics) and theoretical (tissues) values for ρ, RED, RSP and HU. *Abbreviations: GM – Grey Matter; SM – Skeletal Muscle; CB – Cortical Bone*.

Conclusion: 3D-printable thermoplastics are promising tissue equivalents for QA applications in radiotherapy, with mass density and radiological properties closely matching the ones of a variety of biological tissues.

Key Words: Additive manufacturing, quality assurance, radiotherapy.

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Validation of Eclipse eMC using bespoke 3D-printed phantom moulds for electron radiotherapy

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Abstract - Currently, MC simulations of electron beams are considered the most accurate calculation algorithms commercially available for the estimation of absorbed dose distribution and Monitor Units (MUs) calculations [1] [2] [3]. The ionization produced by high-energy (6–18 MeV) electrons beneath cylindrical surfaces of different radii, simulating patient contours, has been previously measured [4] and a later study [4], using eMC, created virtual phantoms with curved surfaces to investigate central-axis dose outputs and per cent depth doses (PPDs). Hence, knowing the importance of adequately validating MC TPS algorithms, this work will aim to model and validate Eclipse's eMC in homogeneous media and investigate the use of 3D printed phantom moulds for dose measurements to validate eMC for a range of clinically-relevant scenarios (different radii of curvature). Three phantom moulds with clinically relevant curvatures (4cm, 10cm, and 20cm diameter) were designed and 3D printed. The moulds are designed to have grooves every 5mm to allow the manufacture of jelly phantoms of different depths. Measurements were performed using a MapCheck device calibrated at different depths for each of the energies (6, 9, 12, 16 and 20 MeV). For 9MeV, using a 10x10 applicator, the measured planar dose distribution at a depth of 4.0cm was compared to the dose simulated using eMC. A 7%/3mm gamma analysis was performed with a 5.0% thereshold. For relative dose comparison the pass rate was found to be 89.1%. It is possible to validate the Eclipse Montecarlo electron beam model using 3D printed moulds to create phantoms of different depths. This method can also be applied to more complex geometries and CT scans of patients can be used to create moulds and jelly phantoms for experimental validation of the eMC predicted dose distribution.

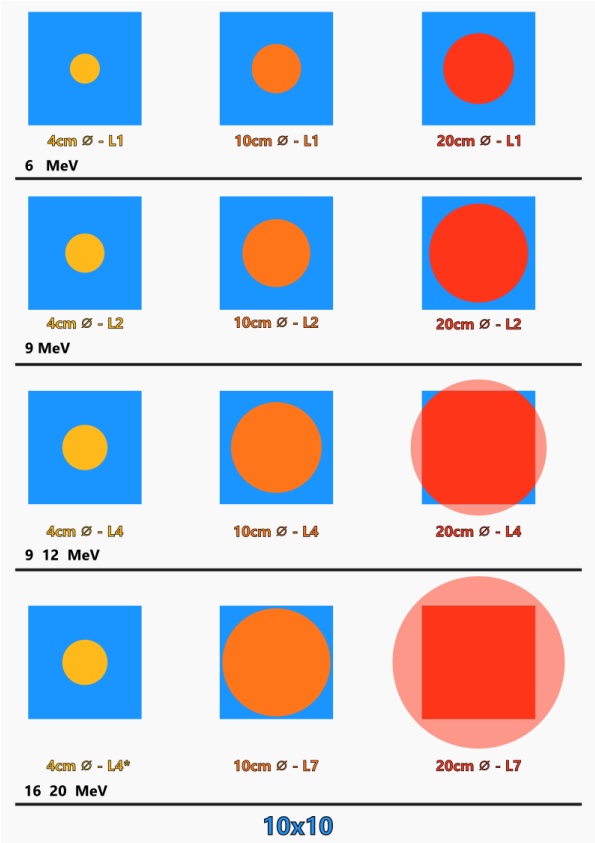

Figure 1. Diagram of top view of different 3D phantoms at 4 different depths. Left to right: 3 different curvatures (4cm, 10 cm, and 20cm diameter). Top to bottom: 4 different depths (L1 = 0.5 cm, L2 = 1cm, L4 = 2cm, L7 = 3.5cm).

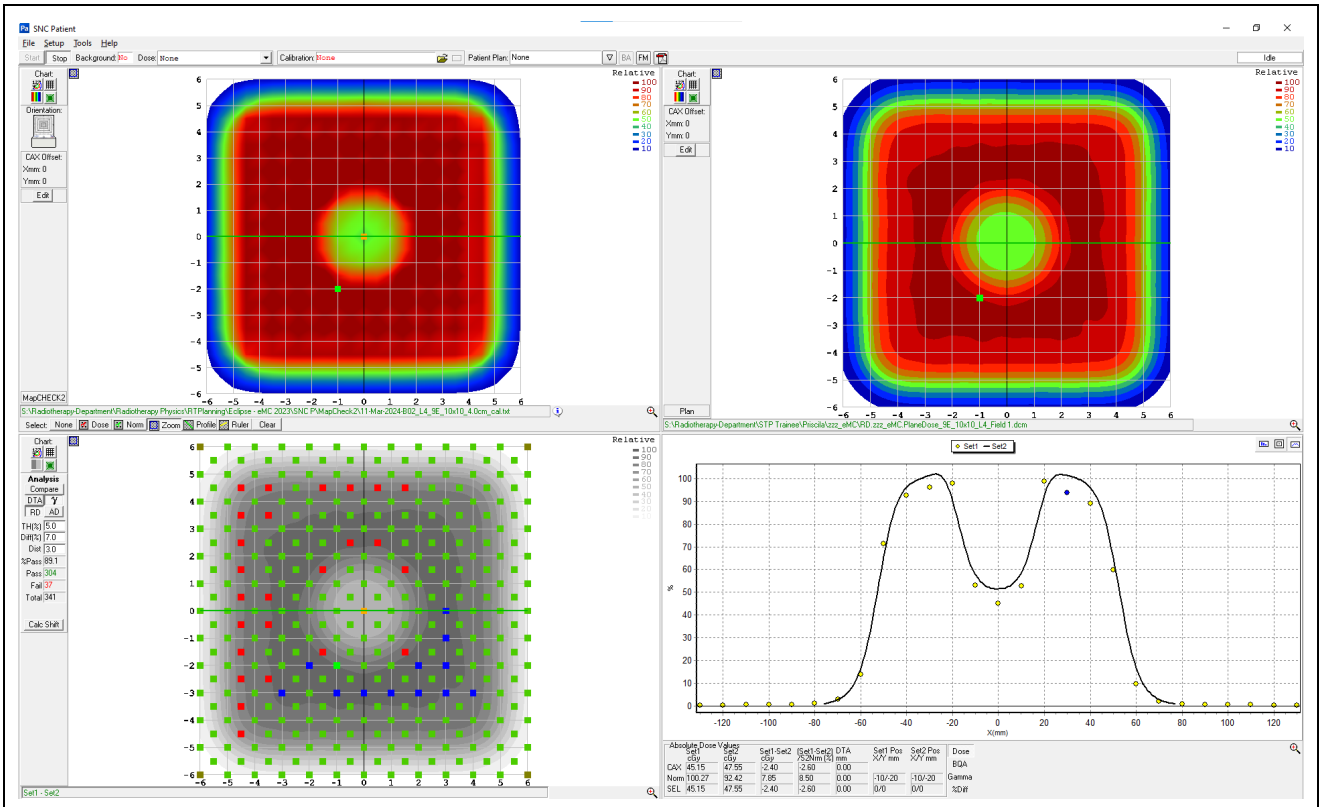

Figure 2. Relatice doses gamma analysis of measured against simulated planar dose distribution for a 9 MeV beam using a 10x10 applicator. Measurements taken at a depth of 4.0cm.

Background. Currently, MC simulations of electron beams are considered the most accurate calculation algorithms commercially available for the estimation of absorbed dose distribution and Monitor Units (MUs) calculations [1] [2] [3]. The ionization produced by high-energy (6–18 MeV) electrons beneath cylindrical surfaces of different radii, simulating patient contours, has been previously measured [4]. The measurements were performed for a range of electron energies, depths, radii of curvature, and off-axis distances. It was shown that ionization ratios (curved against flat surface) may depart from unity by as much as 50% [4]. A later study [4], using eMC, created virtual phantoms with curved surfaces to investigate central-axis dose outputs and per cent depth doses (PPDs). A recent study created personalized 3D printed phantoms based on imaging data, which showed that creating personalised 3D phantoms can be a feasible way to improve the accuracy of dose measurements in electron beams and the confidence in the algorithm [6]. However, the scientific understanding and methodology for clinical dosimetry with electrons in heterogeneous media and irregular surfaces is not well wide-spread or complete, especially if compared with X-ray dosimetry [2].

In view of the above and having regard to the importance of adequately validating MC TPS algorithms, this work will aim to model and validate Eclipse's eMC in homogeneous media and investigate the use of 3D printed phantoms for dose measurements to validate eMC for a range of clinically-relevant scenarios (different radii of curvature).

Methods.

<u>eMC implementation</u> - The implementation of the eMC algorithm consisted of 2 stages: beam implementation and basic validation. PDDs and point dose measurements in water were acquired using a water tank, with a PTW Roos chamber. And, a CC13 ion chamber, in an emptied water tank, was be used to acquire the profiles in air. The eMC algorithm was tested to verify that it can correctly predict the output of the linac in different setups for homogeneous media, for several energies, filed sizes, and SSDs. The difference between the measured and predicted values were within 3mm/3% agreement, hence these were considered acceptable.

<u>Curvature analysis (further validation)</u> - In order to further verify the eMC algorithm, and to comply with IPEM 81 guidance, curved 3D phantoms were be designed. Three phantom moulds with clinically relevant curvatures (4cm, 10cm, and 20cm diameter) were designed and 3D printed. The

moulds will be designed to have grooves every 5mm to allow the manufacture of jelly phantoms of different depths (2.5cm, 3.0cm, 4.0cm, and 5.5cm). The moulds are to be 3D printed and the jelly phantoms will be created filling the moulds at 4 different depths (close to D90 for each energy).

The measurements will be acquired using the MapCheck (Sun Nuclear) device and the measured values will be compared using SNC Patient.To this date, one of the moulds has been printed (two other moulds are in prototype and to be printed in the next weeks).

Results. The beam validation for field sizes, PDDs, profiles, applicator factors and cut-out factors was within 2% of the measured values. The point doses and MUs were within a 5% of the expected values.

For 9MeV, using a 10x10 applicator, the measured planar dose distribution at a depth of 4.0cm was compared to the dose simulated using eMC. A 7%/3mm gamma analysis was performed with a 5.0% thereshold, both for relative (89.1% pass rate) and absolute (72.4% pass rate) doses.

Discussion. The gamma analysis shows a higher pass rate for the relative dose comparison. This was expected given that the MapCheck device requires different calibrations for different energies and measurement depths. But it is important to notice that at the depth of calibration (4.0 cm), in the central region (+/- 2cm) the values agree better than in the peripheral region were the depth of penetration of the beam is different to the depth of calibration. Also, it should be taken into account that eMC showed a disagreement with the measured point doses and hence the absolute dose comparison gives a lower gamma pass rate.

Conclusion. It is possible to validate the Eclipse Monte Carlo electron beam model using 3D printed moulds to create phantoms of different depths. This method can also be applied to more complex geometries and also CT scans of patients can be used to create moulds and jelly phantoms for experimental validation of the eMC predicted dose distribution.

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A Large Area Chest Wall Bolus Print: Problems and Solution

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Background

GenesisCare UK is the UK's leading independent specialist cancer care provider, delivering radiotherapy at 14 centres. In partnership with Print Easy Acrylic Shells, bespoke bolus solutions for various anatomical treatment sites and radiotherapy modalities have been explored.

We present the case of a 31-year old woman with recurrent triple negative poorly differentiated metaplastic matrix-producing adenocarcinoma of the breast, with symptomatic cutaneous metastases over a wide area of the previously-irradiated breast. She was referred for a 36Gy/6# course of radiotherapy over 3 weeks. The size and contours involved for the treatment area presented a challenge regarding how best to treat the clinical target with a definite indication for bolus due to skin involvement.

New technology

The template for the bolus was created using contour information from the patient's planning CT on which the Oncologist had placed markers to represent the Clinical Target Volume (CTV). The Planning Target Volume was CTV+5mm. The treatment plan with the bolus was ready 6 working days after the CT + markup, in line with a standard pathway for a complex VMAT plan with previous radiotherapy.

The bolus structure in .STL format was derived from the DICOM-RT file using a commercial tool. FormLabs® 50A resin with an established tissue equivalence at 6 and 10MV photons was first considered. Printing times, materials and hence cost is directly related to the print volume which increased from an initial indication of 400 to 1350cm^3 and so multiple interlocking sections were considered. However with each section being approximately an 18hour print on a Form 3+ printer this method was abandoned. Instead an ABS plastic shell was printed in four sections, taking 16 hours in total. The assembled shell was filled with an Agar solution and the outer surface sprayed with a water sealant to inhibit evaporation of water. The bolus was prepared in 3 days, it's weight was as expected and a CT scan of the bolus confirmed its uniformity.

The use of a suitably thick custom bolus enabled a VMAT plan to be made, which given the patient contour and history of previous radiotherapy was felt to be the optimal dosimetry to facilitate dose accumulation. Breath hold VMAT was clinically preferred and it was felt to be too challenging to use electrons over the required area.

Lessons learned

The .STL file was extremely large which presented some challenges in transferring data between institutions and ways to minimise file size for large bolus may be beneficial. The best solution for bolus of this size and the printer volume typically available was to print a shell in ABS and fill it with Agar solution. The method and technique of fabrication needs further development.

Best Practice

The planning process to create the bolus and translate that into a complex physical device for use on treatment was executed extremely well. The bolus met the specification and requirements. Planning could continue as the bolus was being printed since it would be exactly to the generated contour's specification.

From a therapeutic radiographer perspective, treatment setup was straightforward and did not require any manual manipulation of traditional bolus or sticking anything to the patient's skin surface which could be uncomfortable and painful when symptomatic. The device offered high reproducibility, stability and conformality with no risk of device failure between fractions. It was comfortable for the patient, well-tolerated, and required very little adjustment once placed which minimised treatment time.

Conclusion

The main dosimetric advantage of this device was its high conformality, with no air gaps allowing for delivery of a VMAT treatment to skin lesions. This device was rigid and perhaps would not be well suited to areas where changes during treatment might be anticipated. In this case, no such changes were anticipated nor did they occur. The overall weight of the device was approximately 1.5kg. This is an important consideration although in this case, the patient did not have difficulty with it as the weight was spread evenly over the area.

Key Words: Bolus, 3D Printing, Radiotherapy, Novel Solutions, Case Study

Case study: 3D printed Motion Capture Pillow for H&N Radiotherapy

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Supervisor: Prof Sanja Dogramadzi, The University of Sheffield

Background

Patient-based focus group studies have shown that patient immobilisation during radiotherapy can cause discomfort, including claustrophobia, which can cause them to move regardless of the restraints used to secure them [1]. This generates uncertainties and can lead to errors, which is usually accounted for by increasing the planned target volume for tumour irradiation (i.e. more tissue is planned to be irradiated to ensure the target tumour cells are annihilated). This can increase the recovery time for the patient [2].

The Motion Capture Pillow (MCP) [3] is being designed as a non-ferromagnetic sensor for tracking patients' movement during H&N cancer treatments and/or MRI scans. It aims to improve patient comfort, and improve the accuracy of the treatment since the tracked motion would be provided as feedback to the radiographer. This feedback can be used to pause the treatment and make the necessary readjustments.

3D printing in the Motion Capture Pillow (MCP)

The skin of the MCP was 3D printed using Objet Connex 260 with the material TangoBlackPlus, to ensure the surface of the pillow stays deformable. The thickness was maintained to be as thin as possible (2mm) and consistent to minimise distortions due to hysteresis. An array (18 x 10) of white pins with 1 cm spacings were printed on the underside of the pillow.

The convex shape of the pillow is maintained via a PID controlled air pressure pump. The device uses computer vision to track the deformations on the surface via the pin deflections from underneath. This is being used to estimate the motion of the object in contact with the surface of the pillow.

Lessons Learned and Best Practices

The current infrastructure cannot withstand 3 to 5 kg weight sustainably. This is how much a human head weighs on average. The material used requires frequent replacement due to wear, a more sustainable material is required for this. Agilus 30 is being considered for the next iteration of this prototype.

Different pin spacings are also being considered to ensure an optimum spacing is used to maintain the accuracy of the motion estimation.

Conclusions

Additive manufacturing provides a benefit to this device to ensure consistency and ease of customisability in its manufacturing process for research purposes, although access to equipment for the manufacturing process has been challenging.

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Scripting a Clinical solution for Silicone bolus 3D-printed casts in RayStation v2023B

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Imperial College Healthcare NHS Trust

Background: In 2022 a local imaging audit of patients treated with bolus identified positional and structural discrepancies ≥ 1cm in all patients treated for lesions in the pelvis (rectum and vulva). A 3D printing solution was proposed as it offers bespoke bolus creation matched to the patient's external anatomy. However, readily available printing materials such as polylactic acid (PLA) were not deemed suitable for pelvic sites due to the rigidity of the material and the sensitivity of the treatment areas. A method for silicone cast creation was therefore pursued.

New Technology or Processes: A script was developed in RayStation v2023B TPS which creates the bolus and a "Bolus cast". As shown in figure 1, the script creates the bolus cast in two/three separate segments that can be exported as .stl files directly from the TPS. This bolus cast is then printed, sealed with silicone glue and filled with a silicone solution. Once hardened, the bolus cast is separated leaving a silicone bolus which closely matches the TPS bolus structure.

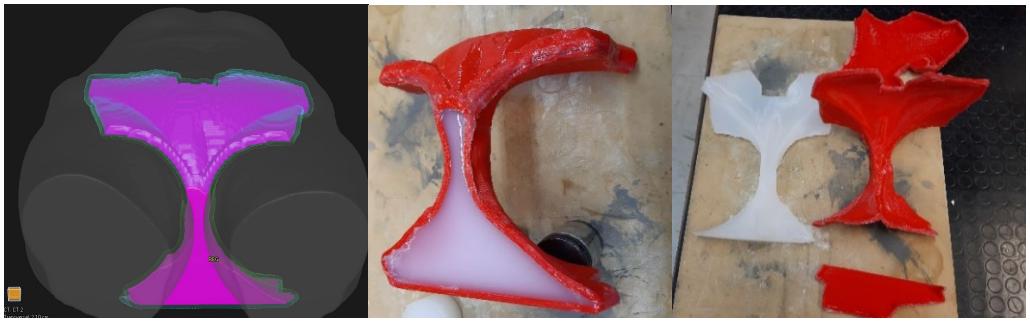

Figure 1: a) TPS structures including External (Grey), bolus (Magenta), and 2 bolus casts (Green?), b) bolus casts printed in PLA filled with silicone solution, c) separated bolus casts and silicone bolus.

In implementing this script for clinical use, considerations were made to ensure compliance with the new medical device regulations (MDR) [1], soon to be released. These included rigorous testing and validation of the script, a thorough risk assessment, robust quality assurance checks (both for each bolus printed and routine script testing) and appropriate methods of documentation for each of these processes. A service evaluation is currently underway to assess the conformity of the silicone bolus to the patient during treatment and differences from the TPS bolus structure.

Lessons Learned: During the testing stage, it was found that full automation of the bolus creation workflow is not feasible, as planner modification of the bolus structure is often required for clinical reasons, and preparatory tasks for casting such as creation of an appropriate hole for filling. The script was therefore designed to allow for user interaction. Careful checking of the bolus structures is also required by the planner, as some segments may be unprintable or unfillable due to their dimensions or those of the resultant support structures required.

A previous H&N 3D Printed bolus evaluation showed that even though the printed bolus closely matches the TPS structure, issues around mark up and set up are still present due to difficulties in indexing. To mitigate this in pelvic bolus, a feature was included in the script to extend the bolus structure posteriorly towards the couch to help stabilise the bolus during treatment set up (this is demonstrated in figure 1a).

Best Practice: Establishing a management system for in-house scripting development helps to mitigate against the risk of printing errors or script malfunctions and comply with medical device regulations. These will be reviewed once the updated regulations are issued.

Conclusion: An in-house scripting solution was developed to create 3D printed bolus casts, which produce silicone bolus that closely matches the planned structures. While the script is able to accurately create a bolus cast, not all will be clinically suitable or 3D printable. User input is always required to review/modify the created structures and their suitability for clinical use.

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