Rapid manufacture of patient-specific, elastomeric, three-dimensional dosimeters using the FlexyDos3D dosimeter

M J Wheatley\textsuperscript{1}, and Y De Deene\textsuperscript{1,2}
\textsuperscript{1}School of Engineering, Macquarie University, Sydney, Australia
\textsuperscript{2}Radiology Department, Nepean Blue Mountains Local Health District, Sydney, Australia

E-mail: Morgan.Wheatley@hdr.mq.edu.au

Abstract. Patient-specific dosimeters are ideal for quality assurance of radiotherapy treatments. Such dosimeters would ideally need to be manufactured in a short amount of time so that the time between initially imaging the patient, treating the patient-specific dosimeter, reading out the dosimeter, and then finally treating the patient, is minimised. 3D printing allows for rapid manufacture of complex 3D objects. The FlexyDos3D dosimeter is a silicone-based material that has enough strength for the dosimeter to hold its shape without a mould or other structure supporting it. A custom 3D printer has been built for making dosimeters from the FlexyDos3D material. Testing of the 3D printer is ongoing.

1. Introduction
Quality assurance of radiotherapy treatments typically rely on point detectors, such as ionisation chambers, 2D films, or 3D dosimeters. 3D dosimeters allow for the dose to be measured throughout the dosimeter in three dimensions \cite{1}. However, most 3D detectors are cast into moulds to provide the shape of the dosimeter required and many of these moulds are of simple shapes, such as cylindrical moulds \cite{2}. Some groups have investigated the use of 3D printers to manufacture the moulds used to hold these 3D dosimeters \cite{3-5}. However, the material printed is not the dosimeter itself and is instead used to mimic the geometry and CT or MRI properties of a patient whilst being filled with a dosimeter. 3D printing of the dosimeter itself would allow for more complex objects to be made that could allow for hollow chambers in the dosimeter, like those in the heart or lungs.

For a dosimeter to be rapidly constructed and match a patient’s anatomy without the use of a mould or container holding the dosimeter, a dosimeter with high strength is required such that the material can stand up under its own weight. The FlexyDos3D three-dimensional dosimeter \cite{6} consists of a silicone matrix which gives the dosimeter strength, and leucomalachite-green (LMG) and chloroform to cause the optical change in the dosimeter that can be correlated to dose.

Silicone, when at room-temperature, takes about 48 hours to solidify but will solidify faster with heat. Therefore, to rapidly set the material, high temperatures are required. The silicone is also a thermosetting plastic meaning that once it sets, it will not melt even with high temperatures, unlike other Fricke gel or polymer gel dosimeters.

A custom-built 3D printer has been constructed that allows for the 3D printing of the FlexyDos3D dosimeter. The printer is still undergoing testing and only simple geometric shapes have been created so far. The dosimeter still shows a dose response when irradiated after printing.
2. Methods and Materials

2.1 Dosimeter recipe
The FlexyDos3D dosimeter consists of a silicone elastomer (Sylgard® 184, Merck) with 4 % w/w curing agent and 93 % w/w base material of the silicone, 3 % w/w chloroform, and 0.03 % w/w LMG (the sum of the percentages do add up to 100.03 % w/w but the 0.03 % w/w difference due to the LMG is seen as negligible). The curing agent and base material are mixed thoroughly first. The LMG is first mixed into the chloroform before that mixture then being stirred into the curing agent and base mixture. Many small air bubbles will be in the mixture due to the stirring. These air bubbles will eventually rise and settle out of the mixture, but a vacuum chamber can be used to speed up this process. Care should be taken when using vacuum to remove the bubbles as the mixture can grow more than three times its volume when the air bubbles in the mixture expand in vacuum. Care should be taken to avoid exposing the dosimeter to bright light and UV sources, or high temperatures to avoid causing the dosimeter to react prematurely.

2.2 3D printer construction
To rapidly cure the silicone dosimeter, high temperatures are required. An oven enclosing the print volume is used to heat the dosimeter once it is extruded out of a nozzle. The oven is heated to a temperature of 160 °C. To ensure that the dosimeter material is not curing inside the tubing whilst it is being pumped into the oven and out of the nozzle, another tube with circulating, room-temperature water surrounds the tubing with the dosimeter material in it. The water is kept at, or just above, room-temperature (22 °C) to avoid condensation on the cooled components which could damage electronics or cause water to get inside the oven enclosure.

The motors used to move the print nozzle are only rated to withstand temperatures up to 60 °C. As such, they cannot be located within the oven enclosure. A delta-style printer configuration was used whereby three pairs of motors are used with all the motors shaft axes oriented in the same direction above the printer (Fig 1). Each pair of motors has an individual moving platform that can be moved up and down a threaded shaft by their respective motor. Each platform then has a set of rods connected to it and each of these rods other ends connect to a central platform that houses the print nozzle. By moving each of these platforms interdependently, the nozzle can be moved in the three-dimensions within the print volume.

As the motors are attached to the oven by their metal shafts, heat can conduct through the shaft into the motor. To keep the motors cool, the same tubing that contains the cooling liquid pumped around the dosimeter material being extruded into the oven is also routed through some custom-built heatsinks which are bolted to the motors. These are used to remove heat from the motors and keep them beneath 60 °C.

A custom printed circuit board (PCB) was made to house the electronics and the microcontroller that controls the printer. The open-source Repetier software (Hot-World GmbH & Co. KG) was used both for the firmware on the microcontroller that controls each of the printer’s operations, and the software on the computer that allows the commands to be sent from the computer to the microcontroller. The software commands are generated from the 3D model on the computer to automate the printing.
Figure 1. A computer 3D model is shown of the printer without the surrounding oven enclosure and the fan to show the printer (a). The motors can be seen mounted above the printer (with the heat-sinks on-top and below) in the delta-configuration. An image of the printer with the electronics control box (bottom), cooling system (far left), extrusion system (syringe and motor assembly to the right of the cooling system), radiator and fans (rear centre), and the printer (right) (b). There is a glass viewing window seen on the door to the printer which allows for viewing of the print job during printing.

3. Results and Discussion

The printer is currently being tested to optimise print speeds, temperatures, nozzle diameters, and layer heights. Basic shapes have been made to test the system, such as hollow cylinders, hollow cubes, and solid cubes. Measurements are being performed on the geometric accuracy of these simple shapes as they are easy to measure and are dependent upon the above parameters.

Photos of a printed hollow cube (made of just silicone for ease of testing) and a solid cylinder and U-shaped object (both made of the FlexyDos3D material) are both shown below (Fig 2). As shown in the pictures, the printed objects do have the rough dimensions of the intended object. However, the side surfaces of the objects are irregular due to the poor accuracy of the current printer mechanics. The U-shaped object was irradiated with a UVC source and a stencil to show the logo of the IC3DDose conference logo to demonstrate the material still reacts to ionising radiation after printing. Further testing is still required to determine the dose response of the dosimeter after printing.

The current material extrusion rate is about 0.3 mL per minute which is on par with many commercial 3D printers. The shown printed objects each took roughly 20 minutes to print except for the U-shaped object which took roughly 40 minutes to print.

Once the mechanical accuracy of the printer is improved, 3D images of patients can be taken, and sections of the patient can be made with the printer.
Figure 2. Photos of some test objects printed by the printer. A hollow cube printed with silicone with dimensions of 4 cm x 4 cm x 2 cm with a wall thickness of 1 mm (a, c). However, due to inaccuracies with the current mechanical setup, the thickness of the walls can vary between 1 mm and 2 mm, as seen by the pattern in the sides of the print (c). A solid cylinder of dimensions 2 cm diameter x 2 cm height and a U-shaped object with dimensions of 5 cm diameter x 1 cm high with a removed inner section of 2 cm width is shown (b, d). A stencil and UVC light was used to irradiate the IC3DDose conference logo into the U-shaped object, demonstrating the printed material is still able to react to ionising radiation.

4. Conclusion

Creating simple-shaped dosimeters for radiotherapy is possible with the FlexyDos3D material and the accompanying 3D printer. Currently, no quantitative irradiations have been performed on the printed objects and the printed jobs have been limited to small, simple shapes. However, it is believed that larger-scale phantoms, the size of the heart or brain, will be able to be constructed once the accuracy of the printed objects can be improved.

The printer can also print silicone material and so has an application to print 3D moulds that can hold other dosimeter material, such as Fricke gels or polymer gels, and form a flexible mould. Deformations can then be performed upon these moulds and the dosimeter inside them.

To minimise print times for larger dosimeters, the external shape of the dosimeter could be printed with the internal structure remaining mostly hollow. The dosimeter could then be filled with more of the dosimeter material.
5. Acknowledgements
The authors would like to thank David Baer, Elton Button, and Walther Adendorff and the MQ METS staff for their consultation and provision of equipment and material in the design and construction of the system.

6. References
[1] Baldock C et al 2010 Phys. Med. Biol. 5 R1-R63
[2] Costa F et al 2018 Phys. Med. Biol. 63 05NT01
[3] Oh D et al 2017 Scientific Reports 7 40922
[4] Ehler E D, Barney B M, Higgins P D et al 2014 Phys. Med. Biol. 59 5763-73
[5] Mayer R, Liacouras P, Thomas A et al 2015 Review of Scientific Instruments 86 074301
[6] De Deene Y, Skyt P S, Hill R et al 2015 Phys. Med. Biol. 60 1543-63