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Original paper

Dosimetry assessment of patient-specific 3D printable materials for HDR surface brachytherapy

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ABSTRACT

Purpose: 3D printable material water equivalence was investigated within the range of Iridium-192 source energies. The aim is to compare the dose calculated by our treatment planning system (TPS) with the dose measured in the presence of printed materials. The purpose of this investigation is to assess the feasibility of using 3D materials for brachytherapy surface applicators.

Methods and materials: Cheetah was examined both in a water tank and with the CIRS anthropomorphic phantom. Calibrated Gafchromic EBT3-V3 film was used and the measurements compared with TG-43 calculations on Oncentra®Brachy. A 3D-printed slab 5 mm thick was created to position the source and two films were irradiated at 5 mm and 15 mm of distance. A curved mould with 7 trajectories was created and coupled with CIRS phantom. A set of CT images of phantom and mould was acquired and imported on TPS, where a target was defined and a dose plan was created. Plan was delivered with two films positioned between two different slabs of phantom, at reciprocal distance of 2 cm, orientated perpendicularly to the source axis.

Results: All PDDs show a maximum difference of 4.7% (average 2.2%). At 5 mm and at 15 mm, the gamma pass rate is 100% with tolerance 2%/1 mm DTA. Results of films placed intra-slabs show a high pass rate (> 99%) with tolerances of 2% dose and 1 mm DTA.

Conclusion: 3D material investigated is water equivalent at Ir-192 energies and agreed with Oncentra®Brachy dose calculations which suggest that it is a suitable material for superficial brachytherapy.

1. Introduction

Superficial kV x-ray therapy (Contact X-ray therapy and Deep X-ray therapy) can be effectively used to treat superficial tumours [1]. However, the treatment techniques can be challenging, particularly for sites where the anatomical surface is not flat. Surface brachytherapy can also be used for superficial treatments, combining a high dose to the tumour volume with a very rapid fall-off in dose for underlying tissue. There is potential for the development of treatment techniques which combine high dose rate (HDR) radionuclides with printed 3-dimensional (3D) materials, to customise the mould at the patient surface to precisely fit the surface of the target area, and minimize air gaps.

Several studies have confirmed the advantages of using patient-specific 3D printed bolus in external beam radiotherapy and electron conformal therapy [2–4] but only two studies [5,6] were carried out for HDR brachytherapy superficial treatments with printable materials.

Oncentra® Brachy, the treatment planning system (TPS) clinically in use for brachytherapy sources, is based on the AAPM TG-43 [9] dose calculation method; which uses Monte Carlo simulations to model the source and calculates the dose in water. The main weakness of this method is the assumption that the material surrounding the source is water equivalent, therefore it does not handle material heterogeneities. In order to introduce a new material in the clinical practice, its water equivalence and suitability must be verified.

The purpose of this work is to compare the dose calculated by Oncentra® Brachy TPS with the dose measured by GAFchromic™ EBT3 films in presence of printed materials. The aim is to evaluate if printable materials can be clinically introduced as surface applicators.

2. Material and methods

2.1. Equipment

HDR brachytherapy treatments are performed using an Ir-192 gamma radiation source (MICROSELECTRON V2, 360 kV average energy), with the Nucletron microSelectron afterloader (Elekta, Stockholm, Sweden). NinjaTek and Airwolf [7] 3D printing materials were considered as they have been previously shown to be water

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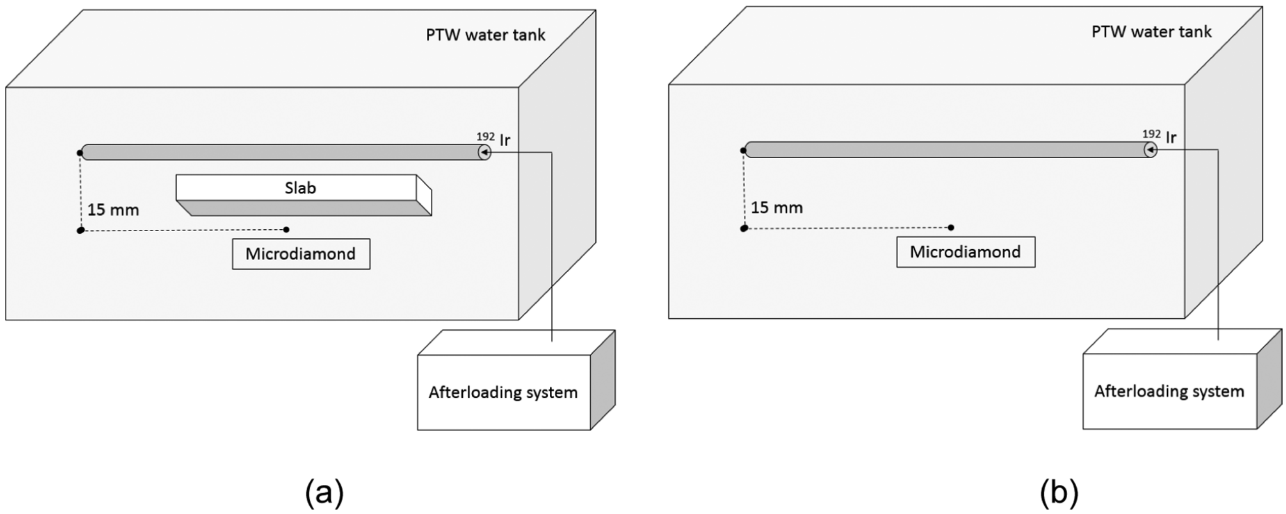

Fig. 1. Setup for the measurements of water equivalence using printable materials (slabs of 10x10 cm^2 flat surface and 5 mm thick), microdiamond and source applicator in water tank. Measurements were compared (a) with slab and (b) without slab.

Table 1
Results from PTW Microdiamond output.

Material	Charge measured (pC)	Deviation with water [%]
Water	187.6 ± 1.0	–
Wolfbend	189.5 ± 0.8	1.02%
NinjaFlex	186.8 ± 0.9	−0.40%
Cheetah™	186.9 ± 0.6	−0.37%

equivalent for external beam radiotherapy [8]. Ashland™ Always Solving (Bridgewater, NJ) manufactures radiochromic films, known commercially as GAFchromic™ EBT3 film. The new generation of films (EBT3-V3), commercially available from August 2013, were used for dosimetry. Films were irradiated with a 6 MV beam produced by an Elekta Precise Linac during the calibration and with an Ir-192 source (via the Nucletron microSelectron afterloader) during validation. Films were scanned with an Epson Expression 10,000 XL scanner, at 150 DPI spatial resolution. Dose distributions were acquired using FilmQA™ Pro software [16] and were compared with calculations by Oncentra® Brachy TPS (Elekta, Stockholm, Sweden). The Gamma analysis method [13] was used as the metric for evaluating the comparison.

2.2. Measurement methods

Recent studies [10–12] have demonstrated that GAFchromic™ EBT3 film is also suitable for brachytherapy dosimetry. Film has an excellent spatial resolution, is nearly tissue-equivalent with an effective atomic number of close to that of water (Z_{eff} = 7.42) [13]. Literature

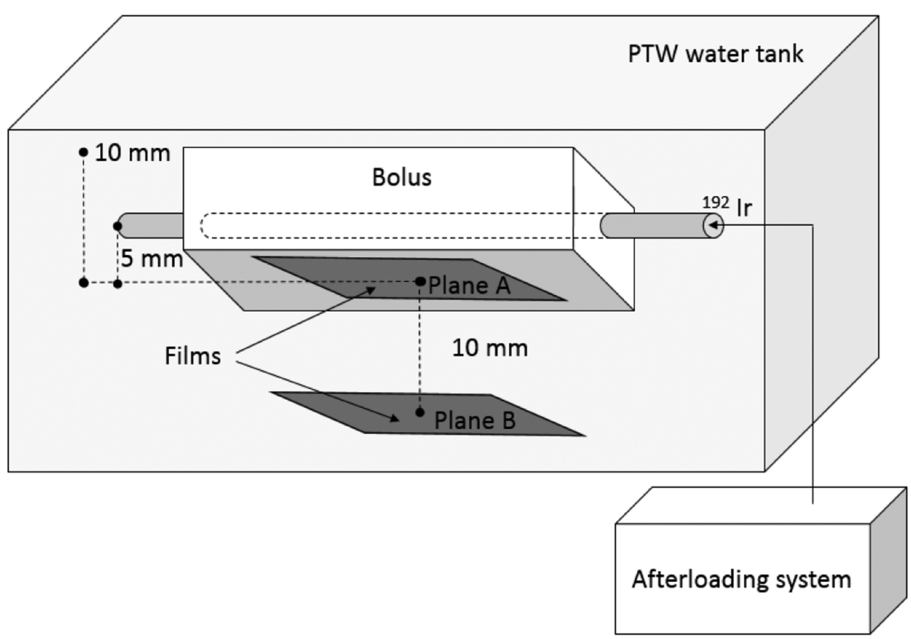

Fig. 2. Schematic representation of the setup used for parallel dose distribution measurements. The dose distribution is acquired with one film in contact with mould (plane A) and the other at 10 mm of distance (plane B). The axis of film is parallel to mould surface and source axis.

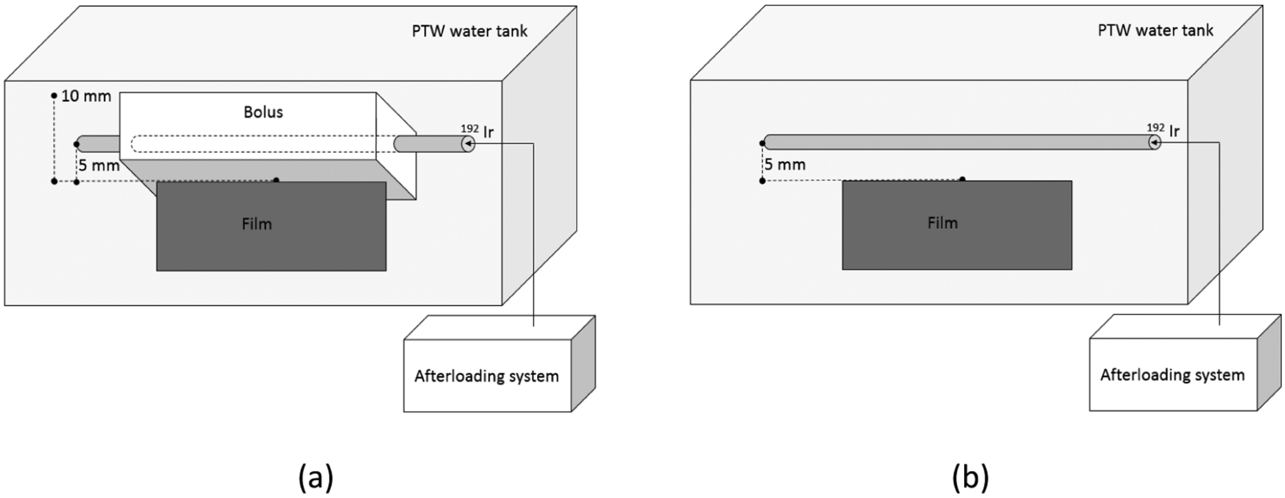

Fig. 3. Schematic representation of setup used for percentage depth dose measurements. The dose profiles are acquired in water (a) with and (b) without the mould. The axis of film is perpendicular to mould surface and source axis.

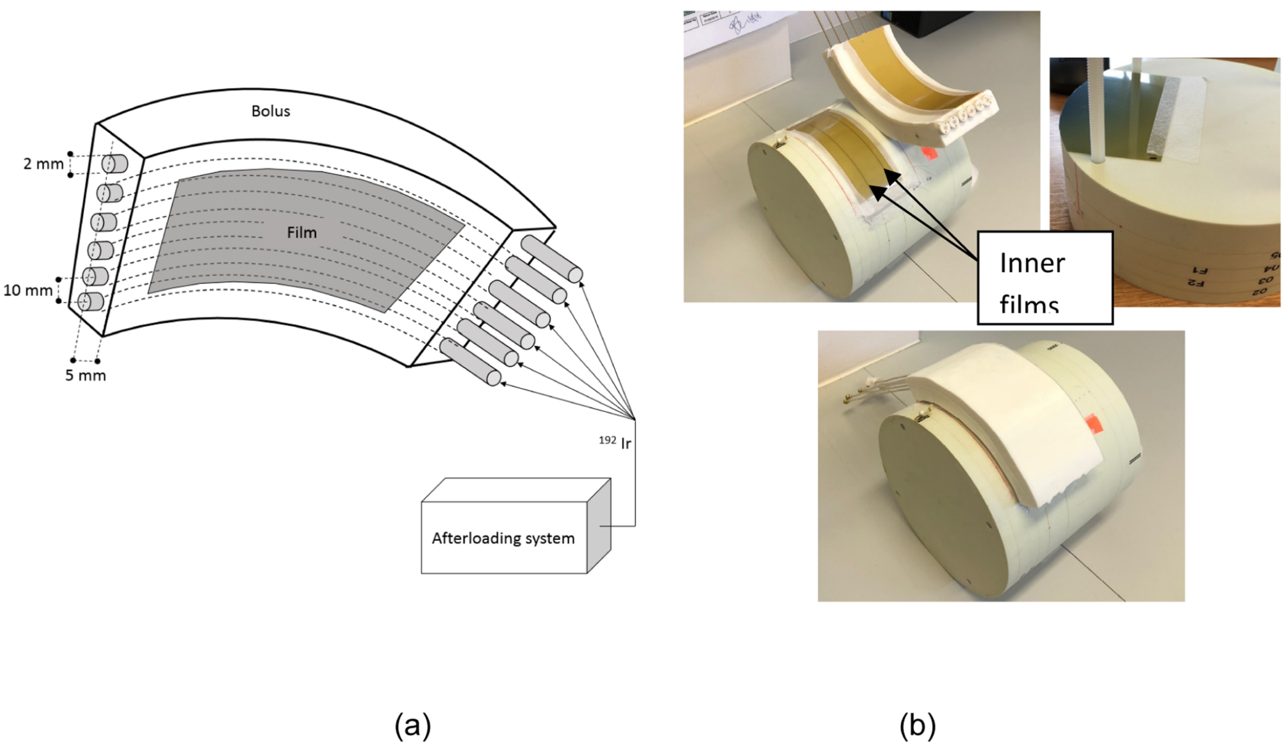

Fig. 4. (a) schematic composition of 3D printed mould and (b) positioning of mould on CIRS phantom. The in-contact surface of mould was created extracting the CIRS phantom surface from CT scans. The figure (a) shows 6 trajectories for the Ir-192 source transfer. Dose distribution onto the surface was investigated using one film placed onto the mould side and the other film onto the phantom side (b). Other two films were placed in between the slices of phantom (labelled in the pictures as inner films), over the irradiated area.

[14,15] validates the use of GAFchromic™ EBT3 films for dose measurements at Ir-192 energies (average energy 360 kV). Tests were performed by this group of authors (see Appendix 1) using GAFchromic™ EBT3-V3 films irradiated in a dose range of up to 9 Gy using a 6MV beam and a 70 kV beam. The results showed that both calibration curves for the GAFchromic™ EBT3 film, agreed within 3%, when the film was irradiated at a dose between 6 Gy and 9 Gy. This range of dose is clinically relevant in brachytherapy. For these reasons film was used in this work to perform spatial dose measurements.

2.3. Selection of material

Three printing materials were investigated and show the following main characteristics [7]:

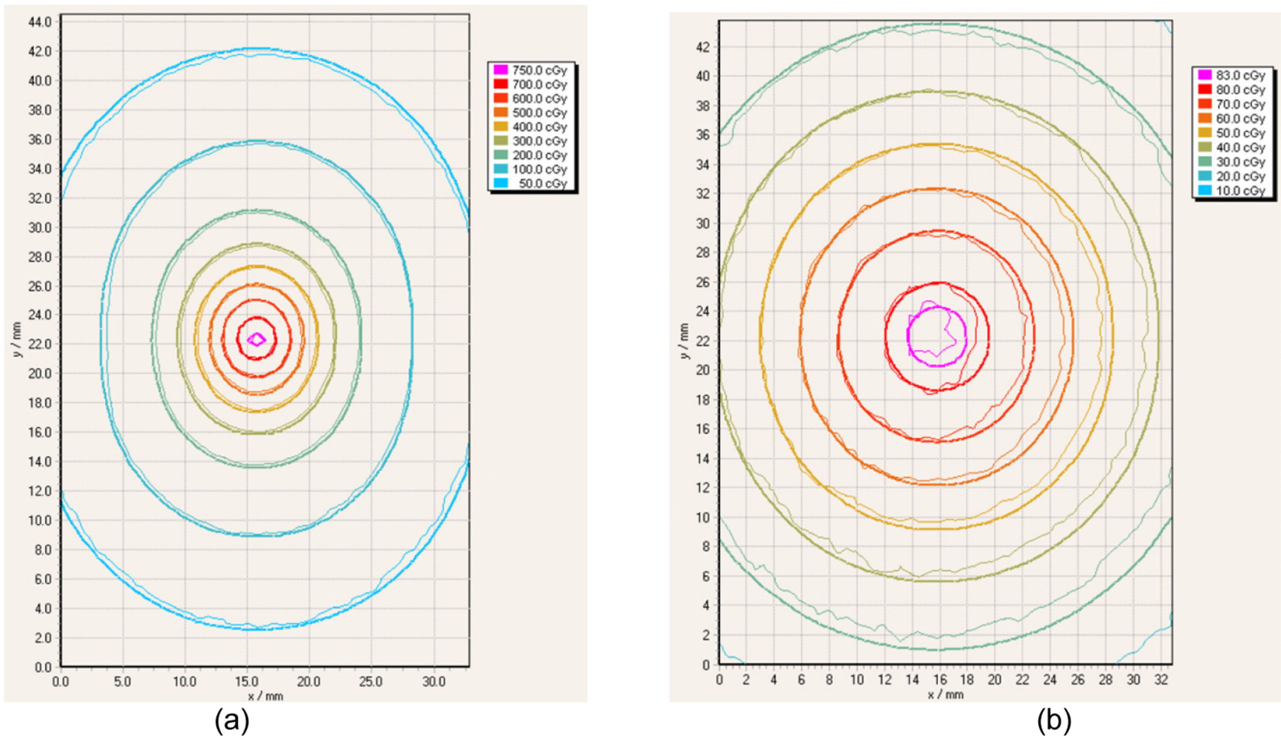

Fig. 5. Planar dose comparison between TPS planned dose (thicker lines) and films measured dose (thinner lines). Film is positioned (a) in contact with mould and (b) at 15 mm of distance from source. The pass rate is 100% with 2% dose and 1 mm DTA.

Table 2
Comparison between absolute dose measurements with GAFchromic™ EBT3 film and calculated dose by Oncentra® Brachy in two clinical points.

	Dose ± standard deviation [cGy]		Difference [%]
	EBT3 Film	Oncentra® Brachy	
Mould in contact	773 ± 38	761 ± 43	1.6%
Mould + 10 mm water	84.5 ± 2.5	84.2 ± 5.1	0.6%

- NinjaFlex (by Airwolf3D)
- Wolfbend (by NinjaTek)
- Cheetah™ (by NinjaTek) has flexibility between that of NinjaFlex and Wolfbend, and is very fast to print. Cheetah™ has also been used clinically in our department [8].

To evaluate the dosimetric characteristics of the three materials, in the appropriate energy and dose range, a PTW 60,019 Microdiamond detector was positioned in a PTW water tank, at a distance of 15 mm

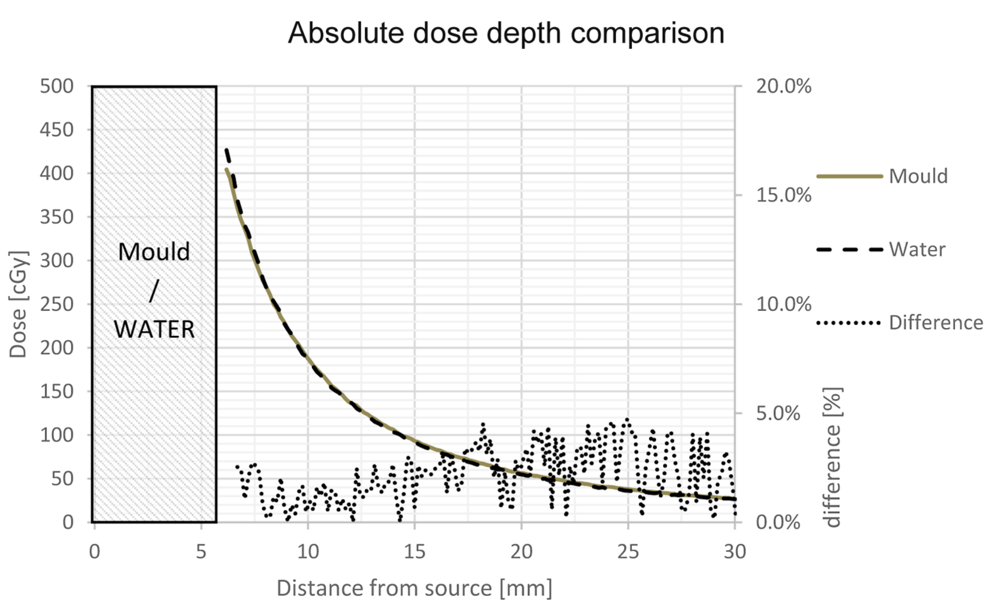

Fig. 6. Comparison between absolute dose in depth with the mould (solid line) and without the mould (dashed line), referred to the left Y-axis. The percentage difference is shown by the dotted line, referred to the right Y-axis.

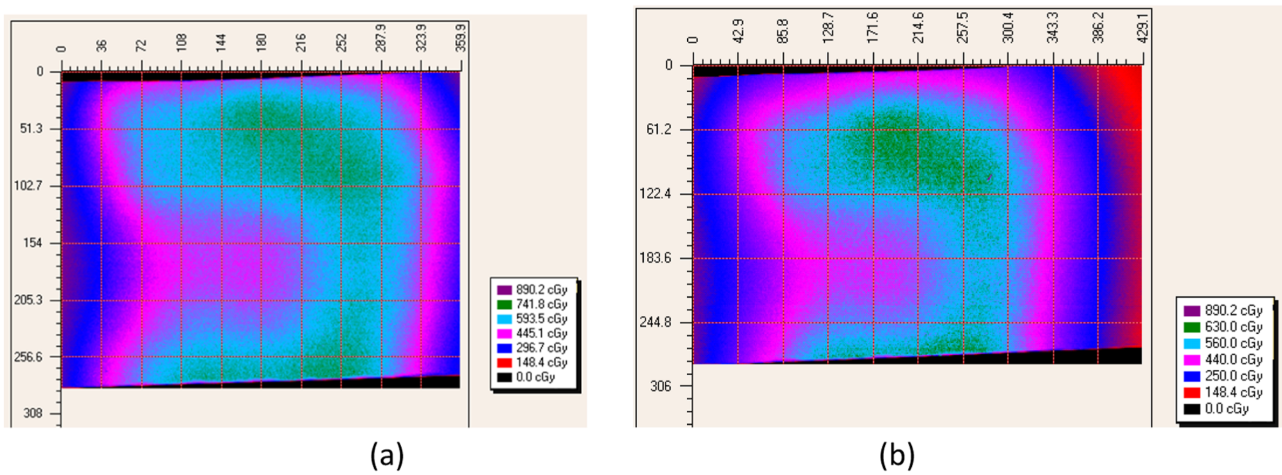

Fig. 7. Dose measurements with film (a) in contact with mould and (b) film in contact with phantom. The dose distribution shape is similar in the two pictures, but there the maximum dose is 14% lower in the film in contact with phantom.

from the Ir-192 source (fixed position); a measurement was taken with a source dwell time of 40 s to minimise the influence of source transfer time (1 s). A sample of each material (10 × 10 cm^2 flat surface, 5 mm thick) was then positioned between the source and the detector and a further measurements was taken (see Fig. 1). Each measurement was repeated 5 times in each case.

Table 1 shows that the maximum differences between any of the materials and water was found to be ~1%, which is within the measurement uncertainty (2%). This low uncertainty was achieved thanks to the repetition of measurements, the controlled slab thickness, the robust positioning of microdiamond to source and the long dwell time.

As there are no significant differences between the three 3D printing materials considered, Cheetah™ was chosen on the basis of its flexibility and print speed. Printed materials using Cheetah™ were then used to evaluate the dosimetric properties, first in a simple geometry and then in a more complex geometry using CIRS Head and Neck phantom model 002HN [17].

2.4. Treatment plan methods

2.4.1. Simple geometry: Flat mould

A sample of Cheetah™ material (10 × 10 cm2 flat surface, 10 mm thick), with one internal trajectory for a HDR catheter at 5 mm deep (see Fig. 2), was created using the 3DBolus App (by Adaptiiv, Halifax, Nova Scotia). Percentage depth doses (PDD) profiles, lateral dose profiles and superficial dose distributions were then obtained using the GAFchromic™ EBT3 film placed in the appropriate geometry relative to the HDR source.

Superficial planar dose distributions were obtained placing one film in contact with the mould surface and another, at a depth of 10 mm in the PTW water tank (Fig. 2). A 3D cubic dose grid was exported from Oncentra® Brachy for the simple plan calculated. The minimum voxel size (1 mm^3) was employed to ensure precise localisation of the correct dose plane for comparison with EBT3 film.

PDDs were obtained with the film in contact with and perpendicular to the mould. A second film was positioned in the same way but without the mould (Fig. 3).

2.4.2. Complex geometry: curved mould

A more clinically relevant geometry was considered using an IMRT head and neck CIRS phantom, which was previously shown to be water equivalent in the energy range 75 keV to 15 MeV [17].

CT images of the CIRS phantom were acquired using a GE CT scanner with 0.625 mm slice thickness and exported to the TPS. Surface contours derived from the CT image set were then used to create the DICOM mould structure. A dedicated software, 3D Bolus App (by Adaptiiv [20]), was then used to generate the required catheter trajectories within the mould structure, and to convert the mould DICOM structure into a stereolithography (STL) file that could be read by the 3D printer application.

The Cheetah™ mould was printed with 6 trajectories of 2 mm width; large enough to insert a catheter for the source positioning (Fig. 4). The distance between trajectories is 10 mm and each trajectory is 5 mm from the phantom surface as per GEC-ESTRO recommendations [18].

Dose distributions and dose depth measurements were performed to validate the treatment plan. Two pieces of film were used for the dose distribution measurements, one positioned in contact with the inside curve of the moulded phantom material and the other film was placed onto the phantom surface (Fig. 4). For depth doses, two films 5 × 5 cm^2 were positioned between two adjacent slabs of CIRS phantom material.

In order to find the position of trajectories in relation to the CIRS phantom interfaces, a new CT scan of the phantom, with the mould in place was performed. A flexible implant tube was inserted in each trajectory and a CT marker set was inserted inside each catheter. The markers length is 288 mm and the tip of marker defines the most distal position of the source inside each trajectory. The images were exported to the TPS where a superficial target of 10 mm of thickness was created, located 5 mm from the surface of the CIRS phantom. The dwell times required to deliver a uniform dose distribution of 4 Gy at 15 mm of distance with the source, covering the whole target, was calculated with the TPS. 4 Gy was selected to keep the area of interest within the calibration curve of the EBT3 film.

Transfer tubes with lengths of 1005 ± 1 mm were used to connect the afterloading system to the flexible tubes, giving a total reference distance of 1293 ± 1 mm.

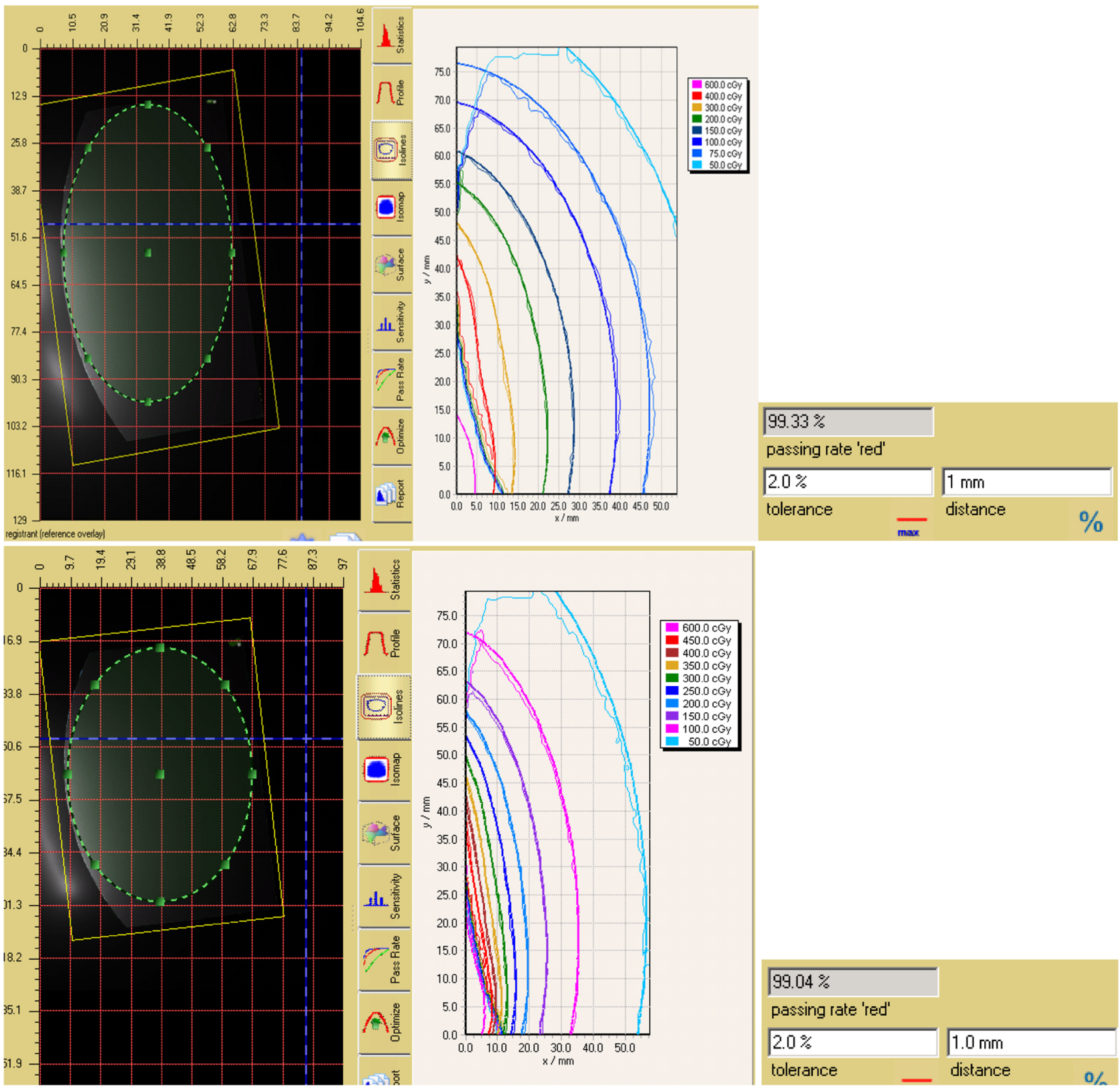

Fig. 8. Comparison between the dose measured with films (thinner lines) and dose calculated by Oncentra Brachy TPS (thicker lines). The films are located between two slabs of CIRS phantom at a distance of 2 cm.

3. Results

3.1. Simple geometry: flat mould

Fig. 5 shows the comparisons between dose distributions measured with GAFchromic™ EBT3 film and dose distributions calculated by the Oncentra® Brachy TPS. Two clinical planes were selected: one located in contact with the mould, resulting in the film being 5 mm from the source (plane A), and the other 10 mm from the mould surface, resulting in the film being positioned 15 mm from the source (plane B) (see Fig. 1). The planes selected are parallel to the mould surface. Using the gamma analysis tool with Film QA pro software the pass rate is 100% in both planes, with a tolerance of 2%/1 mm distance to agreement (DTA).

Table 2 summarizes the results of point A and B, the points of maximum dose in plane A and B respectively, averaged over a $1 \times 1\ mm^2$ area. The differences are 1.6% and 0.6% respectively. Both differences are within the stated uncertainties.

The perpendicular PDD results of the comparison between absolute dose measurements at depth with and without the mould are shown in Fig. 6. The range investigated is the clinically relevant range from 7 mm to 30 mm from the source. The average and the maximum difference are 2.2% and 4.7% respectively.

3.2. Complex geometry: curved mould

The plan was constructed to achieve a homogenous dose distribution in the target, 5 mm below the phantom surface. However, as the dose cubic grid created by the TPS does not geometrically match curved phantom surface, a comparison between dose measured and planar dose distribution calculated is complex. A comparison between the two films coupled together is clinically interesting to investigate, because we can study how the air gaps affect the treatment. Radiochromic film consists of an ultrathin (~28 µm thick) radiosensitive layer, sandwiched symmetrically between two polyester layers (100 µm thick). The distance between the sensitive part of the two film coupled together is 0.25 mm, so a difference of 10% is expected using TG-43 dosimetry datasets [8].

Fig. 7 shows the dose distribution measured with two GAFchromic™ EBT3 films in contact with the mould and the phantom. The dose distribution looks similar but the maximum dose of the film positioned on the mould was 7.4 Gy versus 6.3 Gy for the film positioned on the phantom. The 15% difference is created by both the physical dimension of film (separation of sensitive layers) and a small error positioning (~0.25 mm). The curved surface of the phantom provides a complex shape where the films are located, making the analysis of the dose distributions challenging.

Fig. 8 shows the comparison between the dose measured with the films inserted between the slabs of the CIRS phantom and the dose calculated by the TPS. The distance between the films is 2 cm. The pass rate is > 99% with a tolerance of 2%/1 mm DTA.

In order to maximize the region of interest (ROI) evaluated, gamma analysis is performed in an elliptical ROI 1 mm from the film edge. The spatial position of the film with respect to the TPS plan was found using the FilmQA™ Pro optimizer. The prescription dose at the surface was 5.5–7.0 Gy but, due to the air gap a dose of 4.0–5.5 Gy was delivered at the phantom surface.

3.3. Sources of uncertainty

The AAPM TG-43 formalism provides a reference guide for the analysis of uncertainty arising from the formalism itself, affecting the Oncentra® Brachy TPS dose calculations. The stated sources of uncertainty and their associated values are: air kerma rate (3%), dose rate constant (4.8%), radial dose function (3.5% at a distance of 1 mm from the source, 0% at 10 mm and 4.6% at 50 mm). The total dose-calculation uncertainties are:

- 6.7% at 1 mm
- 5.7% at 10 mm
- 7.3% at 50 mm

There are two sources of uncertainty in the EBT3 film: statistical (type A) and a systematic uncertainty arising from the calibration (2%).

The total uncertainty, calculated using the error propagation theory [19], is 4.7% at 5 mm and 3.7% at 15 mm with a confidence level of 95%.

4. Clinical impact

Due to the steep dose gradient produced by brachytherapy sources, the main issue in the use of Ir-192 in the treatment of cancer is the positioning of the source with respect to the tumour. Superficial tumours can extend 5 mm over the skin and a direct application of the source to the surface is not recommended because it can lead an overdosage of the skin and a corresponding underdosage of the deeper portion of the target. Applicators can position a source 5 mm from the skin; however, at 5 mm from the source, a 1 mm positional uncertainty results in up to a 30% difference in dose deposition, according to TG-43 dosimetry datasets [9].

The use of a mould may be challenging because when it is positioned on the patients' skin it covers the disease, and knowing the path of the source and the disease reciprocal position is only possible with a CT scan. Finding a reproducible position for the mould is the best way to work around this issue. For this reason, flat surfaces should be avoided (e.g. cheeks) and surfaces with curves (e.g. fingers and nose) are preferred.

Air gaps affect the dose prescription in brachytherapy and they must be avoided as much as possible. Acquiring a CT scan of the patient with the mould in place, for planning purposes, is strongly recommended. In this case, the position of target with respect the source trajectories can also be checked.

5. Discussion

The results of this project show that the Cheetah™ material is water equivalent, at the Ir-192 energy. In simple geometry, comparisons between the dose calculated by Oncentra® Brachy and the absolute dose measured by EBT3 films show a pass rate of 100% with a tolerance of 2%/1 mm DTA and the difference between Oncentra® Brachy and EBT3 film in maximum dose is 0.8% and a 1.6%.

The IMRT Head and neck CIRS phantom model 002HN [17] was used to simulate a complex geometry, where the target has an extension of 5 mm over the skin and a uniform dose prescription is requested. The results show a good agreement between the absolute dose measurements of the EBT3 film, inserted between two different slabs of phantom material and the dose calculated by Oncentra® Brachy (> 99% of pass rate with tolerance of 2%/1 mm DTA). The plan created by Oncentra® Brachy was delivered in approximately 10 min, with several source positions and seven different trajectories. These results show the high reproducibility of system: during the irradiation, the actual source position was within 1 mm of the planned position, the dwell time was respected and the correction for the actual reference air kerma rate was respected, within tolerance. The weakness of this simulation is the non-perfect coupling between the phantom and the mould. The physical thickness of the film alone results in a 10% difference in the dose measured between two films coupled together (according to TG-43 dosimetry datasets [9]) but the difference between the two films calculated, at maximum dose point, is 15%. This increase in the dose difference could be attributable to the small positional error (~0.25 mm). Dose differences creating by an incorrect coupling with the mould are not the task of this project and should be investigated separately. However, this is an issue for all surface moulds and is not specific to 3D printed surface moulds. The rigidity of the phantom does not simulate correctly a clinical case because the skin is more flexible and adaptable to the mould. Nevertheless, this is a good indication of the magnitude of the errors arising from air gaps.

6. Conclusion

Cheetah™ (NinjaTek) is a 3D printer material in clinical use as mould material for EBRT in our clinic. This material is easy to print and it was found to conform well to patient anatomy [5]. NinjaFlex (by NinjaTek) and WOLFBEND (Airwolf3D®) seem to have the same water equivalence of Cheetah™, but they are used less frequently due to the increased time required for printing and lack of flexibility respectively.

From the results of this project, Cheetah™ is water equivalent at Ir-192 energy and it is in a dosimetric agreement with TG-43 dose calculations. Due to the rapid dose fall off Ir-192 source, small air gaps affect the dose prescription. CT scan of patient and mould is strongly recommended to check for air gaps or position misalignments.

In conclusion, 3D printing is a precise and reproducible approach to fabricating surface moulds and the materials investigated demonstrate water equivalence. Custom moulds are superior to alternative methods once positional uncertainties are considered.

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Appendix. GafChromic EBT3 energy and dose dependence investigation

Purpose: GafChromic EBT3-V3 films energy dependence is investigated over a range 0.2mmAl HVL − 6MV. The purpose of this work is to determine in which range EBT3 film is independent within the clinically used photon beams and x-ray emitting brachytherapy sources energy range.

Methods: GafChromic films have been irradiated at increasing dose (0 cGy to 850 cGy) with: 6MV beam, TPR (10,20) = 0.684 ± 0.01 generated by Elekta Linac; 70 kV beam, HVL = 2.00 ± 0.01 mm Al, and a very-low-energy beam, HVL = 0.02 ± 0.01 mm Al, generated by Gulmay Orthovoltage unit. The dose output for each beam was determined with an appropriate calibrated ionisation chamber, following IPEM and German protocols recommendations. Using the 6MV calibration curve as reference, the film response in terms of net optical density was evaluated.

Results: the difference in the calibration curve obtained by irradiating the film with 6MV and 2 mm Al HVL energy beams is less than 3%, within the calibration uncertainty, in the dose range 400–850 cGy. The maximum difference is 4% at 150 cGy (see Figs. A1 and A2). The optical density of EBT3 film is significant lower at 0.2 mmAl HVL compared to 6MV, showing differences up to 25%, with a minimum of 16% at 850 cGy.

Conclusion: when the GafChromic EBT3-V3 film is irradiated at dose higher than 400 cGy, the calibration curve for the 2 mm Al beam agrees with the reference beam (6MV) within 3%. A significant under-response (by up to 25%) was seen at 0.2mmAL HVL. 6MV calibration curve could be used with 3% uncertainty for photon energies as low as 2 mm AL HVL.

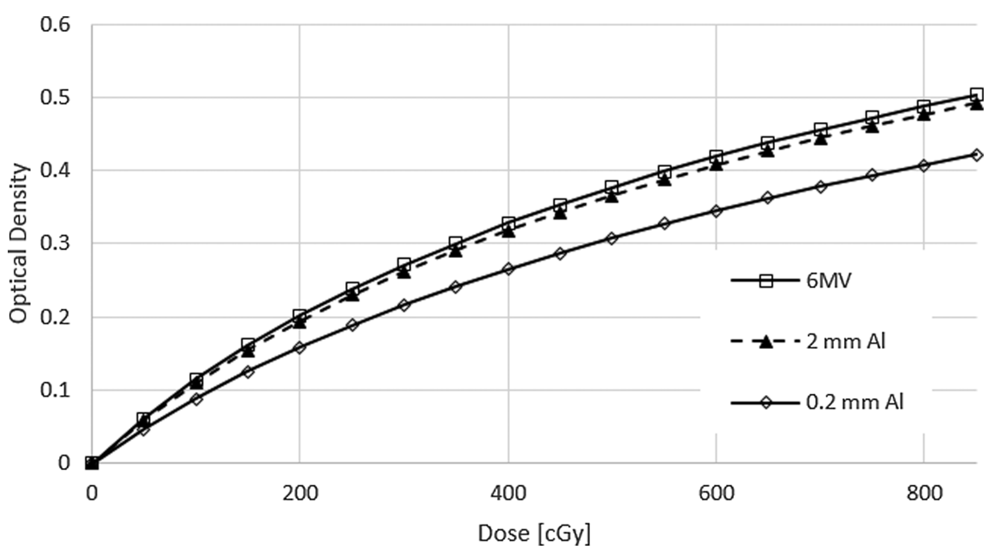
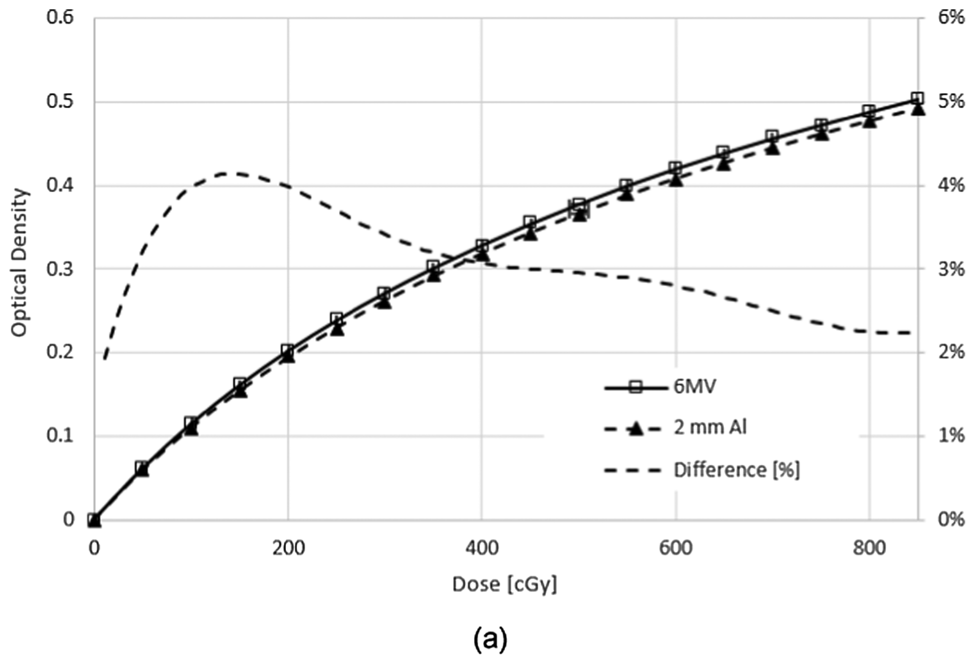


Fig. A1. Optical density versus dose. The film was irradiated at 6MV (squares), 2 mm Al HVL (triangles) and 0.2 mm Al HVL (rhombus).



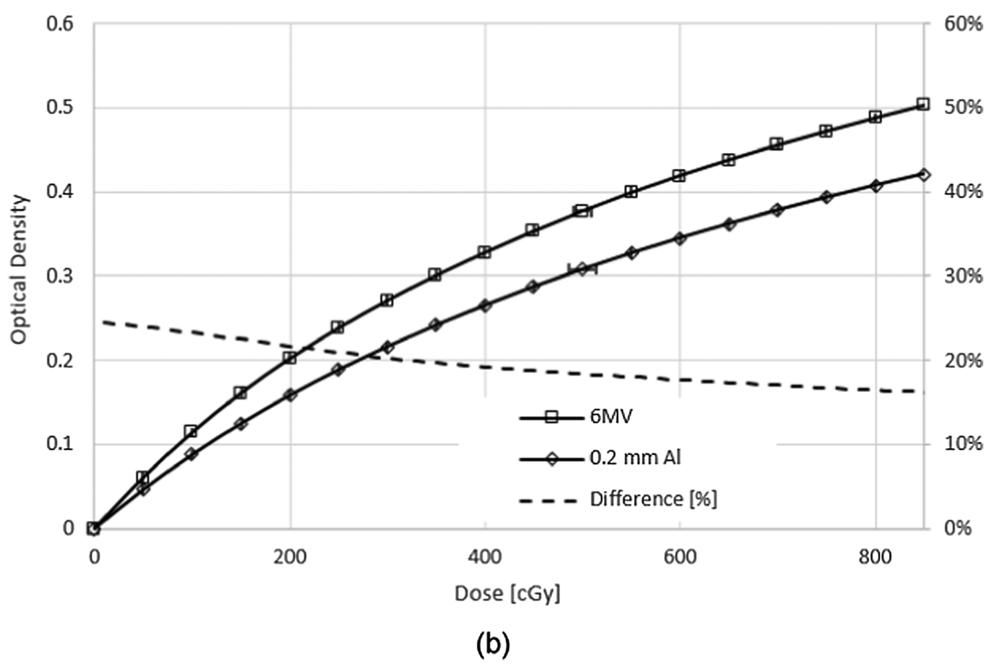


Fig. A2. Percentage difference of optical density versus dose irradiating the films with (a) 6MV, square markers, and 2mmAl HVL, triangles, and (b) 6MV, square markers, and 0.2 mm Al HVL, rhombus. Dotted lines show the percentage difference of optical density. Error bars are reported at 500 cGy.

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Manuals

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