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SCIENTIFIC PAPER

A novel quality assurance system for eye plaque brachytherapy

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Abstract
Eye Plaque brachytherapy pre-treatment quality assurance (QA) conducted clinically involves an activity verification of individual seeds via well chamber and does not include a physical measurement of dose-rate of the final assembly. A novel spectroscopic, dose-rate detection system, was evaluated for pre-treatment QA of eye plaque brachytherapy. The system includes a water phantom with sterility management. The system was calibrated using a known-activity I-125 seed, measured at 1 cm in water along the radial axis, compared to TG-43 U1 calculations and verified over a number of distances. A depth dose curve was acquired for a clinical, mixed activity eye plaque and two 'error' plaques. The probe was stepped from a water equivalent source to a detector distance (SDD) of 2.5 to 12 mm along the plaque central axis. The latter measurements aimed to characterise the sensitivity of the system. The calculated and measured single-seed dose-rates agreed to within 0.5 cGy/h from a SDD of 3 mm and above. The clinical plaque showed agreement between measured and treatment planning system (TPS) calculated dose-rates within 2%. Sensitivity testing resulted in a maximum deviation from TPS data of 18%, therefore was able to detect the presence of packing errors. The dose-rate detection system was successfully evaluated for verification of I-125 based eye plaques without compromising sterility, allowing for quick pre-treatment, dose-rate verification of patient-ready plaques. Its agreement with TPS data for the unmodified plaque and its deviation when introducing errors confirms the approach suggested is a viable QA tool.

Keywords Brachytherapy · Spectroscopy · Diode · Eye plaque brachytherapy

Introduction

Eye plaque brachytherapy can be used for the treatment of small and medium-sized ocular tumours, with survival rates consistent with enucleation [1]. Treatment is commonly conducted using Iodine-125 sources, which have a primary photon emission of approximately 27 keV [2]. Dose delivery is achieved by placing the eye plaque adjacent to the treatment volume and the total duration of treatment is determined by measuring the average activity of the sources. Clinical dose-rates range between approximately 0.60–1.05 Gy/h [3].

AAPM task group 129 (TG129) reviewed the dosimetry of eye plaques for intraocular tumours, finding that for an average treatment prescription of 85 Gy at 5 mm depth in a homogenous medium, just 75 Gy was actually delivered during treatment [4]. The relationship between the cumulative activity of the seeds and dose-rate is formalised in the update to AAPM task group 43 (TG-43), however clinical eye plaque brachytherapy conditions depart from ideal measurement conditions, suggesting a need to advance plaque dosimetry [5]. Any potential QA protocol is problematic as each component of the plaque must remain sterile prior to patient implantation. Currently, no dose-rate measurements of the loaded plaque are taken to verify the dose-rate of the plaque and conformance to the TPS plan [6].

Some studies have utilised gel dosimetry as a means to measure the dose of a clinical eye plaque [7]. Advantages of gel dosimetry include a high spatial resolution and can achieve a close proximity to the plaque. However gel does not have an instantaneous read-out and the signal acquired is dependent on the time spent in contact with the radiation source, often taking hours to acquire a usable signal. Maintaining the sterility of the plaque during the pre-insertion QA would also prove problematic.

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Dosimeters such as film and TLDs have also been used in the context of TPS verification of eye plaque brachytherapy planning [8]. Similarly to gel, film and TLDs require time to process the signal due to dose and can only obtain an integral measurement. Uncertainties of approximately 5% are expected when using these dosimeters [8]. A review of literature found the existence of QA devices for eye plaque QA is currently limited and many centres offering the treatment have developed bespoke systems based primarily on using the above dosimeters [9], outlining a clinical need for a new QA system that could increase efficiency and help standardise practise.

A previously published silicon dosimeter designed for eye plaque QA was shown to be accurate at a distance of 1 cm from the plaque surface, but was ultimately found to be unsuitable due to substantial angular dependence and included no provisions to maintain a sterile plaque environment [10, 11]. Presented in this paper is the new iteration of that system, which aimed to accurately determine the dose-rate of a clinical plaque and to develop a measurement apparatus that addresses the unique challenges involved in eye plaque brachytherapy quality assurance.

Method

Equipment

ROPES eye plaque

The Radiation and Oncology Physics and Engineering Services, Australia (ROPES) 15 mm eye plaque includes an acrylic insert, holding up to 10 seeds, and a stainless steel applicator. The insert serves to position the seeds 1 mm from the sclera of the eye in two concentric rings about the plaque central axis, as seen in Fig. 1. The stainless steel applicator is a spherical shell that encapsulates the mould, shielding normal tissue from treatment photons.

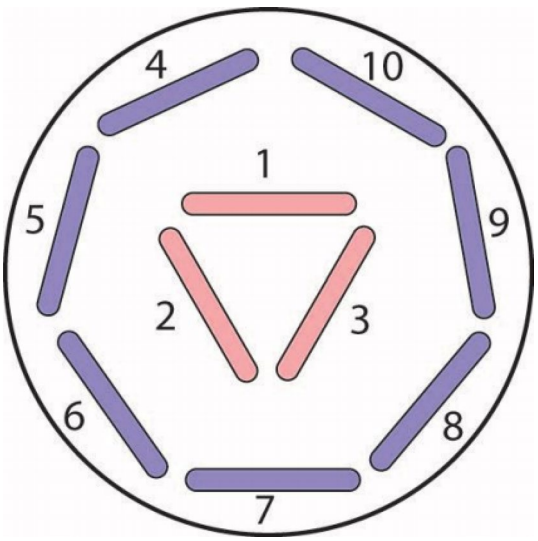

Fig. 1 15 mm ROPES eye plaque. Positions 1–3 are make up the central ring of seeds and positions 4–10 are the outer ring

Edgeless silicon diode for dosimetry

The eye plaque brachytherapy probe was constructed using an 'edgeless' diode, shown in Fig. 2. The sensitive volume has dimensions of 0.5 mm × 0.5 mm × 0.1 mm and is operated in reverse bias at − 4.5 V. As per its edgeless design, the N + electrode encapsulates most of the silicon substrate volume of the diode, minimising its angular dependence to within ± 2% over 360° [12]. The high resistivity of the substrate (10 kΩ cm) allows operation of the detector at low bias with no deterioration of its charge collection efficiency.

The diode is mounted to the tip of a PCB, containing a field effect transistor for initial signal amplification and a preamplifier circuit for transmission to the microprocessor unit. This circuitry is housed within a 3D printed plastic cover, placing the sensitive volume 1.5 mm from the external surface of the probe tip. The packaged probe can be seen in Fig. 3.

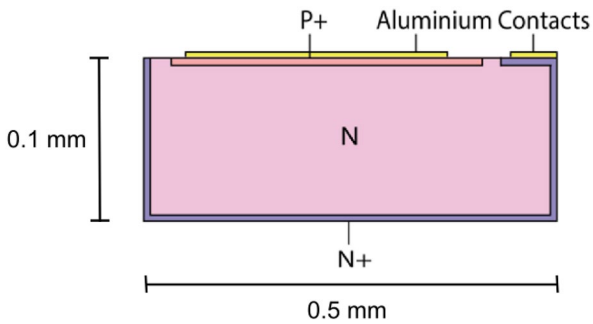

Fig. 2 'Edgeless' diode design

Fig. 3 Eye plaque brachytherapy QA probe

Microprocessor unit

As shown in Fig. 4, the Microprocessor unit was used to interpret and process the amplified signal from the probe. The unit contains a shaping amplifier, on-board microprocessor as well as adjustable inputs for accurate calibration.

A pulse-by-pulse detection mode was employed, enabling spectroscopic analysis of the signal and the setting of a manual energy threshold. Previous studies concluded the Iodine-125 brachytherapy seed spectrum can be averaged such that each pulse can be counted as a 27 keV event [13]. This approximation, which facilitated fast signal processing, is valid due to the relative symmetry of the spectrum and average energy occurring within the most intense photopeak. The microprocessor approximates all counts above the energy threshold to this same energy, enabling the system to have fast processing times and a linear dose response. The gain of the unit was adjusted during calibration to relate this signal to dose. The energy threshold is set such that low energy scatter, characteristic X-rays from metallic probe components and electronic noise can be filtered out, resulting in a more accurate and reliable reading.

Phantom/motorised stage

A cylindrical water phantom with height 140 mm and a diameter of 175 mm was designed and fabricated from 3D printed Visijet Crystal. For short-ranged I-125 photons, the phantom is effectively an infinite water bath and hence satisfied TG-43 U1 assumptions. The tank contains a waterproof void where the plaque is held during measurements, extending out from the base of the tank into the centre of the water bath as seen in Fig. 5. The plastic membrane separating the plaque chamber from the water is just 0.5 mm thick, a limitation of the 3D printer and materials adopted, and is a hemisphere in shape to conform to the ROPES 15 mm plaque curvature.

Fig. 4 Microprocessor unit

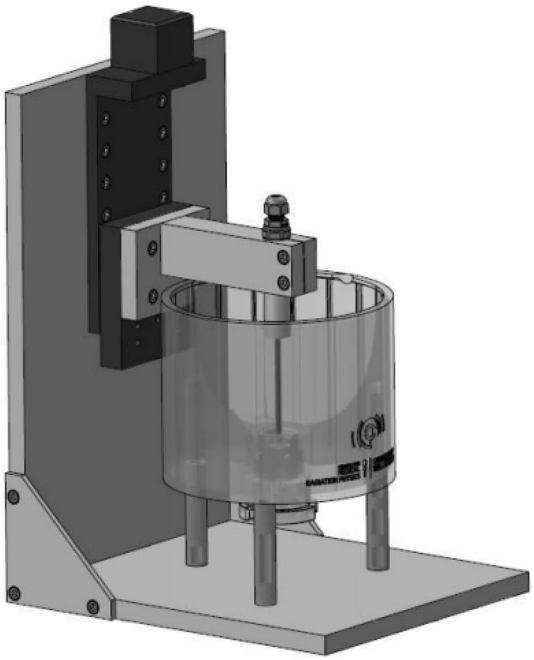

Fig. 5 3D render of full QA system, including the phantom, linear stage stand and probe in measurement position

To preserve the sterility of the eye plaque for surgical insertion, a plug was designed to house and position the plaque in the waterproof cavity under the water bath, as seen in Fig. 6. The plaque is placed in the curved receptacle of the plug and is secured with a 0.5 mm thick retaining cap, resulting in a total thickness of 1 mm of plastic between the detector tip and the plaque surface. A minimum distance of 2.5 mm between the sensitive volume of the probe and surface of the plaque exists during sterile measurement. The plug is screwed into the cavity and locked into

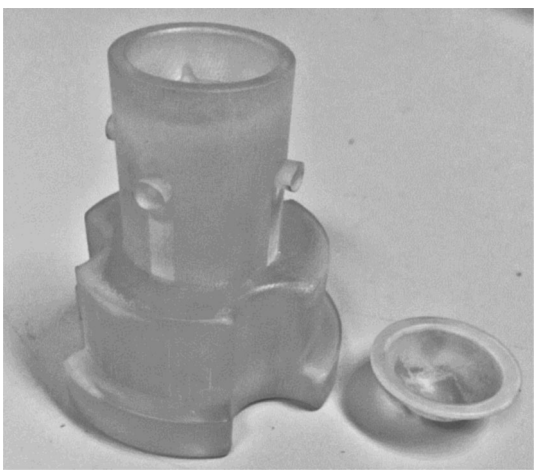

Fig. 6 Eye plaque housing and retaining cap

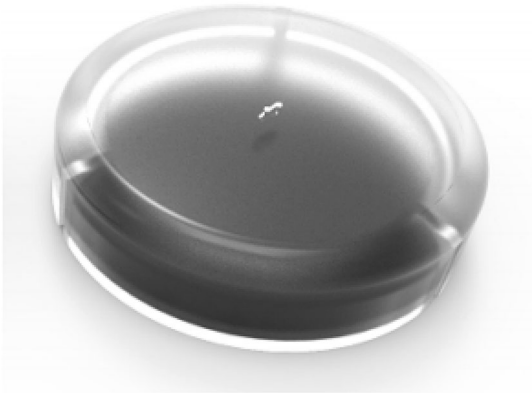

Fig. 7 Calibration cap

the measurement position. Due to their modular and distinct design, these 3D-printed components are able to be sterilised.

Prior to dosimetric measurements, accurate dose-rate calibration is necessary. This process requires the measurement of a single seed in the water phantom. A 3D printed calibration cap was designed to ensure reliable positioning of the seed shown in Fig. 7. This cap was designed to sit in the water bath of the phantom and resulting in a minimum distance of 1.5 mm between the sensitive volume and seed surface.

A linear stage was used to position the probe vertically along the central axis of the plaque and facilitated accurate and reproducible positioning of the probe relative to the surface of the eye plaque. The minimum step size capability is 1 mm. The phantom and stage can be seen in Fig. 5.

Calibration

Calibration of the eye plaque verification system involves adjusting the gain of the signal processing system such that the dose-rate displayed matched that of a single seed source.

The activity of the calibration seed was measured with a traceable well chamber and used to determine the dose-rate at a distance of 10 mm along the source central axis. This seed was then inserted into the calibration cap and secured within the water tank. Using the linear stage, the probe was lowered into the water bath until the external tip of the probe made contact with the seed, establishing its reference home position. Due to the 1.5 mm separation between the probe tip and the actual detector, the probe was raised 8.5 mm, placing the sensitive volume 10 mm from the cap. The gain of the read-out system was adjusted to match the dose-rate (cGy/h) determined using the previously measured seed activity with the well chamber.

The response of the detector was characterised post-calibration by measuring the dose-rate of the seed as a function of distance. Measurements were undertaken between 0 and 12 mm from the seed surface with 0.5 mm increments. The calibrated dose-rate profile was compared to TG43 U1 calculations, as shown in Fig. 8. Good agreement was observed for all measurements at a distance greater than 2 mm, with slight probe misalignment suspected to be the cause for deviations at shorter distances. Alternatively, attenuation of the 3D-printed, plastic cover of the probe maybe have altered the spectrum relative to water, at a close proximity, reducing the dose-rate. In addition, there are relatively large uncertainties for distances of less than 2 mm from the seed surface in TG-43 U1 tabulated data, of approximately $\pm 4\%$.

Full plaque measurement

The eye plaque verification system was evaluated using a 10-seed clinical plan. A loaded ROPES plaque was positioned in the waterproof cavity of the water phantom and placed in the measurement position. The probe was moved to its reference position and the dose-rate measured at 0.5 mm increments up to 12 mm from the plaque surface. Due to the additional plastic layers of the phantom, the minimum distance between the plaque surface and the detector was 2.5 mm.

Sensitivity testing of the quality assurance system was conducted by introducing a variety of packing errors into the 10-seed plaque. The plaque was packed using a mixed distribution of 3.841 mCi and 1.556 mCi seeds, as per the clinical plan, however a single central high activity seed was replaced with a seed of the lower activity. A second scenario was tested with seeds of a similar activity, 4.022 mCi and 1.652 mCi, where a low activity seed positioned in the outer

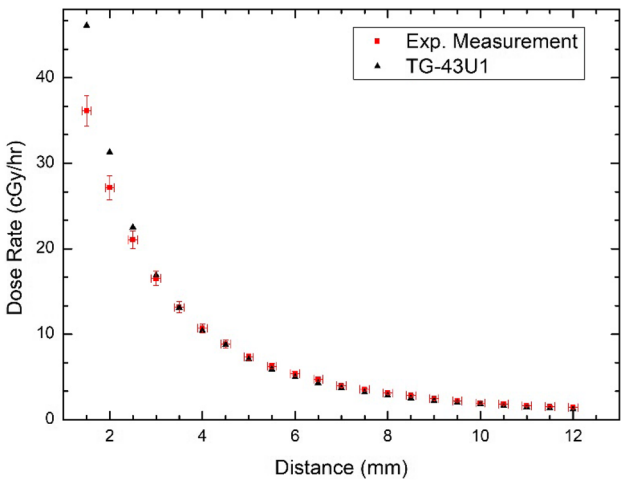

Fig. 8 Dose rate comparison of TG-43 U1 calculations and experimental measurements of a single seed

ring was replaced with a high activity seed. A diagram of the seed positioning can be seen in Fig. 1.

To evaluate the uncertainty of experimental measurements, a minimum of three independent readings, were acquired per read-out position and the standard deviation of the mean determined.

Results

Clinical plan verification

Figure 9 shows a comparison between the measured dose rates using the eye plaque verification system and the calculated values from the TPS for the correctly loaded 10-seed plaque. Measured dose-rates agree with all TPS values between 3 and 13 mm, with a maximum deviation of approximately 2% when the detector tip was closest to the plaque. At this position, I-125 photons are incident on the sensitive volume at a solid angle of approximately π steradians subtended by the source on plaque surface, as the detector was located inside the concavity of the plaque. Therefore the 2% discrepancy between planned and measured dose-rates are consistent with the uncertainties of tabulated dose-rate data in close proximity to brachytherapy seed surfaces and the angular dependence of the edgeless diode design [12].

Central ring packing error verification

Figure 10 shows a comparison of measured and planned dose rates for the 10-seed plaque, with a high activity, central seed replaced by a seed with a lower activity. Measured dose rates were significantly lower than planned values at distances 2.5–6 mm, with a maximum deviation of 18% at 2.5 mm. The deviation between measured and planned values decreases as a function of distance due to the short range of I-125 photons, resulting in very small discrepancy in photon intensity between the planned and measured case at large distances.

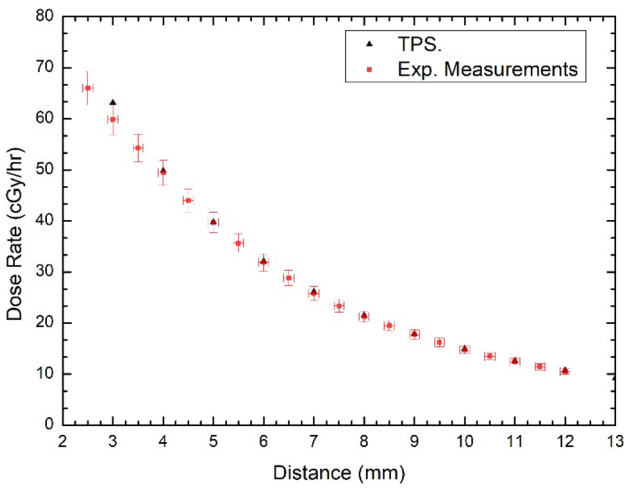

Fig. 9 Dose rate comparison of a clinical plan and the experimental measurements of a clinical eye plaque

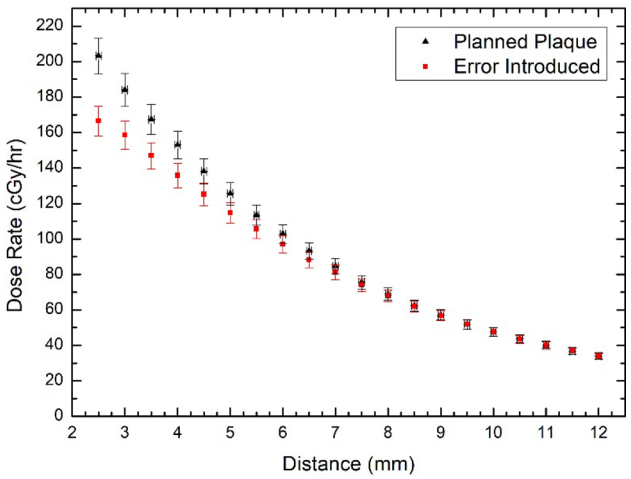

Fig. 10 Dose rate comparison of a plaque packed according to the TPS and a plaque where a 3.841 mCi inner ring seed was replaced by a seed with an activity of 1.556 mCi

Outer ring packing error verification

Figure 11 shows the comparison of measured and planned dose rates for the 10 seed plaque, however with a lower activity seed replaced with a high activity seed in the outer ring of the plaque. Measured dose rates exceeded planned values by approximately 6–9% at all measurement locations.

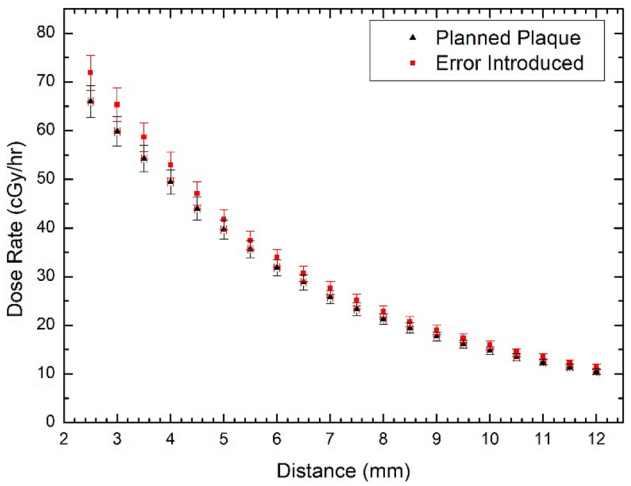

Fig. 11 Dose rate comparison of a plaque packed according to the TPS and a plaque where a 1.652 mCi outer ring seed was replaced by a seed with an activity of 4.022 mCi

The sensitivity of the QA system is such that it can detect a misplaced seed in outer ring of the plaque, which relative to the useful range of I-125 photons, is significantly further from the detector than a centrally located seed.

For both error verification cases, the observed discrepancies would warrant the clinical physicist to unpack the plaque and use the well-chamber to remeasure each individual seed to verify their activity, and to ensure the correct seed placement in the plaque before treatment could commence.

Discussion

The clinical eye plaque dose-rate dosimetry system has acquired depth dose curves in close agreement to both TG-43 U1 for a single seed case and the TPS for a clinical planned plaque within 1% and 2%, respectively. This includes measurement points in close proximity (< 5 mm) to the radiation source, in a region where preceding publications have reported results with limited dosimetric agreement to theory. Jarema [10] reported deviations between TG-43 U1 calculations and measured dose-rates to be just 1% at 10 mm from the surface of the eye plaque, however deviations of up to 15% were discovered at distances of less than 5 mm and were attributed to significant angular dependence of that dosimeter [11].

As demonstrated by the small discrepancy between calculated depth dose and measured values of the clinical eye plaque at shallow depths (Fig. 9), there still exists some angular dependence in the new probe. However, there are also significant uncertainties involved in the measurement of low energy sources such as I-125, due to the extremely sharp dose gradients they exhibit. Therefore, an accurate determination of the diodes sensitive volume position and distance is required for eye plaque QA using this spectroscopic dosimetry system, followed by the precise calibration as used in this work.

The shallow depth region has been shown to be clinically significant as the largest deviations measured in the 'error' plaques were present at distances below 5 mm. As the intent of the dosimetry system was to perform quality assurance on clinical plaques, accuracy and reliability of measurement of the dose in regions most sensitive to variation is crucial.

The QA system calibration method depends on the linearity of microprocessor, such that a one point calibration remains valid over the range of measurements. Uncertainty in the dose linearity of the system may be attributed to a suboptimal placement of the energy threshold, particularly in the presence of electronic noise. In addition, the discrete timing characteristics of the pulse-by-pulse detection may also introduce uncertainty in the dose rate. The system does not include an on-board background signal compensator. Under very high dose-rate conditions the micro-processor does have a risk of dead time and pile up, as one pulse is being processed, another may have been generated, but not counted. The result of this would be an underestimation of the dose-rate, most likely present at close proximity to the photon source.

Another source of uncertainty was the 3D-printed phantom composition. Visijet plastic is proprietary, therefore the exact composition of the material is unclear and the impact of non-water equivalent material was difficult to quantify. The close conformance of experimental result to theory for both a single seed and a clinical plaque, suggests that for a I-125 spectrum, the material is approximately water equivalent, albeit with a slightly higher density as could be expected by a polyethylene based plastic. The calibration method may also account for any energy dependence of the material, as acquisitions are normalised to 10 mm and can be compensated by the gain settings.

It is recommended that clinical implementation of the fast read-out, spectroscopic dosimeter includes the measured dose-rate at both shallow and larger depths to be compared with the corresponding TPS values, ensuring an accurate and reliable depth dose verification.

Conclusion

The eye plaque brachytherapy QA system developed has been shown to be a viable clinical tool for dose-rate verification of eye plaques prior to patient insertion. The system displayed the ability to detect even single-seed plaque packing errors, in both the central and outer sections of the plaque while maintaining plaque sterility. No other QA solutions currently available measure the instantaneous dose rate of a clinical plaque prior to patient insertion, in addition, other dosimeters require large signal acquisition, calibration and analysis time, while the system presented offers fast, stream-lined measurement output. Despite small uncertainties in detector localisation and the presence of an air gap in the detector tip, the calibrated system achieved a 2% agreement with TPS calculations at 2.5 mm from the plaque surface and can easily discern introduced dose-rate deviations.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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