Improvement in the accuracy of polymer gel dosimeters using scintillating fibers

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Abstract. We propose a novel method for the absolute calibration of polyacrylamide gel (PAG) dosimeters with one or more reference scintillating fiber dosimeters inserted inside the gel. Four calibrated scintillating fibers were inserted into a cylindrical glass container filled with a PAG dosimeter irradiated with a wedge filtered 6 MV photon beam. Calibration curves using small glass vials containing the same gel as the cylindrical containers were used to obtain a first calibration curve. This calibration curve was then adjusted with the dose measured with one of the scintillating fibers in a low gradient part of the field using different approaches. Among these, it was found that a translation of the gel calibration curve yielded the highest accuracy with PAG dosimeters.

1. Introduction

The possibility of inserting scintillating dosimeters inside gel dosimeters has been suggested before [1]. We extended this work by evaluating different procedures for calibrating the gel dosimeters using the information provided by scintillating fibers as reference dose points.

2. Materials and Methods

2.1. Scintillating fiber dosimeters setup and calibration

The scintillating fiber dosimeters consisted of a 2 mm long by 1 mm in diameter BCF-12 scintillating plastic fiber (peak 435 nm). The scintillators were coupled to plastic optical fibers (length 13 m, diameter 1 mm, ESKA™ Premier polyethylene jacketed, Mitsubishi). The surface of the scintillating end of the optical fibers was manually polished and then glued using cyanoacrylate. Finally, the unjacketed end of the fibers were painted black using aerosol paint, dried at least 24 hours and inserted.
into a gel dosimeter. The scintillating dosimeter is thus entirely made of plastic and is considered almost water equivalent [2].

The other end of the optical fibers was held in front of a color CCD camera (Apogee Alta U2000c) inside an aluminum box following the design of Lacroix et al. [3]. This box enabled the precise alignment of multiple fibers in front of the CCD camera with the possibility of removing and accurately repositioning the fibers in front of the camera, thus retaining the fiber calibration. The box was placed behind the maze in the irradiation bunker away from the radiation source. No measurable noise appeared during irradiation such that filtration of the optical signal was not needed.

Dosimeters were placed in front a 6-MV photon beam (300 MU/min, Siemens Oncor Impression linac). The daily machine output was verified before every experiment using an ionization chamber in a 10 × 10 cm² square field in plastic water. Five fibers were irradiated in a water tank in a 10 × 10 cm² square field and in a 40 × 40 cm² square field with the fiber rolled in the field to maximize the production of Cerenkov light within the fibers following a published methodology [4]. The green and blue channels of the CCD camera were exploited for chromatic discrimination [5,6] of the signal such that calibration factors could be found for the subtraction of Cerenkov light. Each irradiation was repeated 5 times and the CCD pixels corresponding to each fiber were averaged to improve the signal-to-noise ratio. Black noise was removed by collecting data in the absence of radiation; the data were averaged and subtracted from the data acquired during irradiation. After completion of these calibration steps, the extremity of each fiber was placed into a custom made closed plastic box to avoid dust deposition that could alter the light transmission properties.

2.2. Gel mixing
Polyacrylamide gel (PAG) dosimeters were mixed in an oxygen-free environment. Gelatin (5%) was slowly mixed in deionized water (89%) at room temperature and then heated to 45°C in approximately 10 min with a hot plate and stabilized at this temperature. When the gelatin was completely dissolved, N,N’–methylenebisacrylamide (bis, 3%) and 3 acrylamide (aa, 3%) were added to the mixture and stirred until complete dissolution.

A borosilicate cylinder (height of 19.7 cm and inner diameter of 5.7 cm) was constructed with 4 entry ports placed at 1.2, 2.9, 5.5, and 9.2 cm from the bottom of the cylinder. Rubber tubes were connected to the ports to prevent the gel from flowing out of the cylinder. A scintillating fiber dosimeter was inserted through each port and centered inside the cylinder. The warm gel solution was transferred into the cylinder, and inside 13 glass calibration vials (height of 3.5 cm and diameter of 1.16 cm). The filled cylinder and vials were immediately immersed in water and placed in a refrigerator for approximately four hours. The samples were next transferred into a room temperature water bath for temperature stabilisation for four more hours.

2.3. Gel irradiation and imaging.
The cylinder was laid on its side on a Plexiglas support in a water tank with the gel surface at 2 cm below the water surface (SSD 100 cm). The cylinder was placed perpendicular to the linac arm and oriented such that the fibers were perpendicular to the beam. The cylinder was positioned such that the entry port at 1.2 cm was at the edge of the field.

Three measurements were made with different prescribed doses and using physical filters of 45° and 60° on a 6MV photon beam to obtain a notable variation of the dose inside the gel. A square field of 10 × 10 cm² at the surface of the water was used. The vials were irradiated with a square 10 × 10 cm² field in a water tank at various depths along the field axis. The dose given to the vials was verified with an ionization chamber and one vial was kept unirradiated.

After irradiation, the samples were stored in the MRI room for 24 hours and then scanned with a Siemens Sonata 1.5 T MRI system. The cylinder was placed in a custom made styrofoam holder designed to fit tightly and reproducibly inside the head coil. A multi-slice multi-echo sequence was used (TR = 7750 ms, TE = 40 ms, 16 echoes, 12 averages, FOV 192 mm × 96 mm, slice thickness = 4
mm and a matrix of $256 \times 128$. The last 14 echoes were fitted with a monoexponential function on a pixel-by-pixel basis to produce maps of $T_2$ (and $R_2 = 1/T_2$).

Finally, another calibration of the scintillating fiber dosimeters was performed for verification. Discrepancies of the dose from the gel irradiation are below 2% when comparing the dose calculated using the calibrations before and after irradiation.

The water tank and the cylinder were scanned in a Picker PQ5000 CT scan using a chest protocol in the position they were irradiated. The data was then transferred to the Pinnacle³ 8.0m planning system to simulate the dose distribution in the cylinder. Measurements inside the cylinder were made with an ionization chamber (Exradin A12) to verify the validity of the planning system. The measurements were made using water instead of gel. The measured dose was 0.8% higher than the simulated dose. Pinnacle³’s simulation is thus used as the reference dose distribution except in the high dose gradient at the field edges.

2.4. Gel calibration

A first calibration curve was generated using the $R_2$ values of the vials and the dose values obtained by an ionisation chamber. Then, the dose given by the scintillating fiber dosimeters are correlated to the $R_2$ values around the scintillating dosimeter. A margin of 1.5 mm is ignored around the fiber because of possible susceptibility artefacts or altered gel response. The calibration points (and curves) of the measurement with the 45° wedge are shown in Figure 1.

Four calibration methods were tested:

Method #1 A “vials only” calibration curve.

Method #2 A linear fit between the $R_2$ value of the unirradiated vial (0 Gy) and the $R_2$ value around a scintillating fiber.

Method #3 Adjusting the slope of the “vials only” curve to match the $R_2$ values around the fibers (while maintaining the 0 Gy value).

Method #4 To vertically shift the “vials only” curve to match the $R_2$ values around the fibers.

Figure 1. Calibration points and curves obtained from the calibration vials and from the fibers inserted into the gel. Only one fiber measurement (third black square from the left on the graph) is used to adjust the calibration curves from the vials for methods #2, #3 and #4.
3. Results and Discussion
Our first observation was that the data from the fiber at the edge of the irradiation field were not useful. The large dose gradient in this location prevented a precise estimation of the $R_2$ value around this fiber; those data were not considered further. The dose difference between the “vials only” calibration and the fiber measurements was around 13%. The latter agreed to within 3% with Pinnacle³’s simulation. For this test, only the fiber (at 5.5 cm of depth) closer to the center of the field, was used to modify the calibration curves.

In the center part (80% of the full width at half maximum) of the profile shown in figure 2, the mean absolute difference with Pinnacle³ is 12.4%, 1.4%, 1.2% and 0.9% for methods 1 to 4, respectively. The results show that it is possible to obtain a more accurate dose when inserting a scintillating fiber inside a PAG dosimeter combined with a set of irradiated vials. The error falls below 2% compared to Pinnacle³ in the central zone of the field for the last approaches.

4. Conclusion
Inaccuracies up to 12.4% were obtained in polymer gel dosimeter phantom calibrated using small glass vials. We showed that inserting a scintillating fiber inside the radiation field away from an important dose gradient could correct these inaccuracies. A useful and practical method consists in a translation of the calibration curve from the vials to match the calibration point from the scintillating fiber. This reduced the inaccuracies to below 3%.

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