

Pushing the boundaries of spatial resolution in dosimetry using polymer gels and radiochromic films

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Abstract. Advanced radiotherapy and brachytherapy techniques are raising the bar for detectors with respect to high spatial resolution. Dosimetry based on most point-like dosimeters, e.g. diamond detectors or small volume ionization chambers cannot be used efficiently and accurately for detecting 2 or 3D-dose variations at millimeter scale. Hence radiochromic films and polymer gels with high two/three-dimensional resolution provide a good verification tool for measuring dose distributions of very small collimated beams. In this study the performance of film and gel detectors in detecting the very fine dose distributions generated from collimation holes of four different sizes is investigated. Pencil beams with diameters down to 0.455 mm could be resolved by both detector types comparably.

1. Introduction

Current advances in stereotactic radiosurgery, intensity-modulated radiotherapy and image-guided radiation therapy as well as steep dose gradients of brachytherapy applicators call for an increasingly high spatial resolution in dosimetry [1-8]. While conventional radiation detectors (e.g. small volume ionization chambers, diodes or diamond detectors) show significant uncertainties due to their relatively large sensitive volumes [9] or non-equilibrium conditions as a consequence of non-water equivalence of the detection material or electrical equipment, polymer gels [10] and radiochromic films are well suited for this application because of their intrinsically high resolution and their near water equivalence. This study will compare the dose imaging results of these detectors with respect to collimated pencil beams with field sizes of 0.455 mm – 1.925 mm.

2. Materials and Methods

2.1. Polymer gel preparation and calibration

The normoxic polymer gel was manufactured in-house at normal atmosphere oxygen concentration levels. It consists of gelatin, methacrylic acid, ascorbic acid, copper-sulfate and distilled water [10, 11].

The calibration was performed in a single-scan approach as proposed by Oldham *et al* [12]. The BAREX container was placed in a water phantom with a source to water surface distance (SSD) of



100 cm in a 6 MeV electron beam and irradiated to a known dose, which was validated with a Roos chamber (PTW-Freiburg, Germany). From the well known depth dose curves of the 6 MeV electron beam provided by an Elekta Synergy linear accelerator (LINAC) a number of calibration data points were obtained in a range of 0 – 30 Gy.

The MR imaging was performed on a 7 T scanner (Siemens, Germany) equipped with a MR-microscopy imaging gradient system [13, 14]. The achieved in-plane pixel size was $156 \times 156 \mu\text{m}^2$ with a slice thickness of 1000 μm . All gel containers were scanned following identical protocols using a multiple spin-echo sequence with 20 equidistant echoes ($\text{TE} = 10 \text{ ms}$). For the evaluation T2 images were extracted. The pixel values from the T2 weighted images are transformed to relaxation rates R2. The data points of the calibration are plotted on a dose versus R2 plot and a polynomial fit was applied to convert the R2 images into dose maps.

2.2. Radiochromic film and calibration

For this study Gafchromic EBT3 (ISP Technologies Inc., Wayne, NJ, USA) are used from the same lot (# 11041302) following published guidelines [15]. To account for post-exposure darkening [16] the films were scanned 24 h after irradiation. All films were scanned on an EPSON Perfection V700 scanner using Epson Scan software with a color depth of 48 bit and a resolution of 150 dpi resulting in a pixel size: 0.169 mm. The pixel scanner values (SV) of the more sensitive red color channel [17] were transformed to net optical density (netOD) values using the following formula [18]:

$$\text{netOD} = \frac{\text{SV}_{\text{BG}} - \text{SV}}{\text{SV}_{\text{BG}}}$$

where SV_{BG} is the average pixel grey value from red color channel of the un-irradiated film and SV being the averaged scan value in a $2 \times 2 \text{ cm}^2$ region of interest of the irradiated calibration films.

For calibration $4 \times 4 \text{ cm}^2$ film pieces were placed in a solid water slab phantom and exposed to eight dose steps from 0 to 25 Gy in a Co-60 photon beam. The mean netOD of each calibration film was related to dose and fitted using a fourth order polynomial.

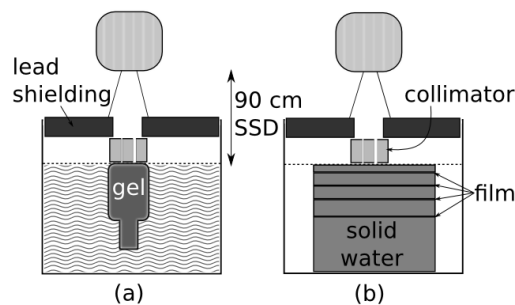


Figure 1. Setup for the collimated pencil beam for the polymer gel (a) and radiochromic film (b).

2.3. Measurements with pencil beam collimator

The polymer gel filled BAREX containers were positioned upside down in a water phantom at a SSD (source surface distance) of 100 cm with the bottom of the container at water level (see figure 1). A block of 10 mm thick lead (see figure 2) with four holes of different diameters (1.925 mm, 1.540 mm, 0.910 mm and 0.455 mm) was used to collimate a 6 MV and a 10 MV photon beam from a LINAC with a $5 \times 5 \text{ cm}^2$ field size. To further avoid dose contributions from aside, additional lead absorbers were set next to the central leaden hole-absorber as shown in figure 1.

A similar setup was used for the film irradiation with identical SSD (= 90 cm). Six film strips of $4 \times 4 \text{ cm}^2$ were positioned between slabs of solid water of 2 mm, 5 mm and 10 mm thickness. The first film was located at a depth of 2 mm. The central axis of the pencil-beam collimator block was placed

above the center of the films on top of the first solid water slab. Similar measures as for the polymer gel were taken to avoid scatter irradiation.

The LINAC was set to deliver 4000 MU and 3000 MU for the polymer gels and radiochromic films, respectively. These settings were chosen in order to achieve doses in the high sensitivity range of the polymer gel and film dosimetry.

3. Results and Discussion

The netOD, originating from the scanned extracted red-channel of an irradiated film and a T2 weighted image of the polymer gel, both in a depth of 12 mm, are shown in figure 2. The dark spots in both images indicate that the pencil beams at all sizes down to 0.4 mm can be identified in both detectors. Because of the limited thickness of the absorber both detectors receive a level of dose outside the collimation holes. For the film the background dose is 20.50 ± 0.14 Gy and for the polymer gel it is 26.93 ± 0.37 Gy. In the peak of the largest pencil beam (1.925 mm) doses reach up to 24.69 Gy and 31.44 Gy, respectively.

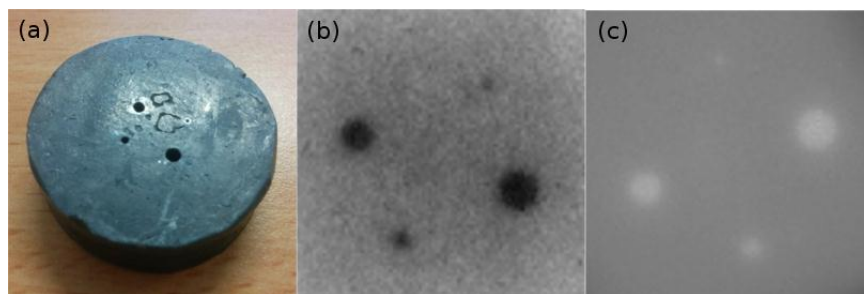


Figure 2. The lead collimator with the four different sized collimation holes (a) and the resulting scans of EBT3 film (b) and R2 map of the MR scan (c) of a slice in 12 mm depth for the polymer gel.

Profiles perpendicular to the incident beam in a depth of 12 mm from the surface for all four pencil beams are shown in figure 3. The calculated dose data from the measurements obtained with the polymer gel and radiochromic film are fitted to a Gaussian equation using MATLAB. The baseline was considered to be the average dose value in the vicinity of the normal distribution outside the primary pencil beam. The fitted curves were used to center the data points around the presumable center of the collimation holes. The normalized relative dose profile of the smallest pencil beam shows a very noisy signal in which the dimension of noise in the background dose level is up to 40 % (film) and 20 % (gel) of the dose signal in the peak of the pencil beam.

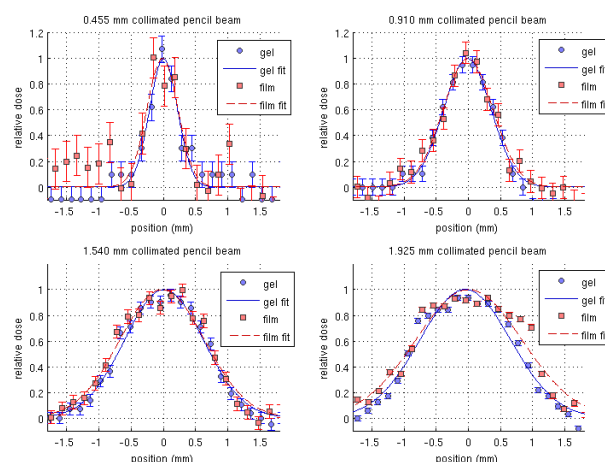


Figure 3. Comparison of dose profiles obtained using polymer gels and EBT3 films across collimated pencil beams of various widths. Error bars indicate the average standard deviation in the background signal outside the

peak.

Table 1 shows the full width at half maximum (FWHM) values of all four pencil beam sizes and compares the FWHM obtained with gel and film to the nominal sizes of the holes in the collimator block. While for the three smallest pencil beams the FWHM values with both detectors are larger than the actual size of the holes, in case of the largest pencil beam (1.925 mm) the Gaussian fitting algorithm underestimated the width of the hole. However, as can be seen in figure 3, the single Gaussian was not the best fitting algorithm. The gel measurements yielded generally narrower pencil beams (figure 3). This tendency of smaller FWHM values might, however, be in the range of the level of uncertainty and hence be caused by the noise in the data. Further studies need to be performed to confirm this trend in the future. This is also represented by lower FWHM values in table 1.

Table 1: FWHM values for the different sized pencil beams across the x-axis perpendicular to the incident beam with the first standard deviation according to the error bars shown in figure 3.

Nominal size of collimator (mm)	FWHM (mm)	
	Polymer gel	Radiochromic film
0.455	0.513 ± 0.045	0.566 ± 0.047
0.910	0.875 ± 0.010	0.920 ± 0.031
1.540	1.510 ± 0.007	1.551 ± 0.024
1.925	1.755 ± 0.051	1.953 ± 0.010

The maximum dose modulation in terms of difference in signal between dose in the peak and background was typically slightly higher with polymer gels than in films. The difference might be related to the edge enhancement effect [19] seen for these types of gels [7]. The largest pencil beam (1.925 mm) yielded dose modulations of $\Delta D_{\text{gel},1.925\text{mm}} = 4.36$ Gy and $\Delta D_{\text{film},1.925\text{mm}} = 4.04$ Gy. For the smallest pencil beam (0.455 mm) the corresponding dose modulations were: $\Delta D_{\text{gel},0.455\text{mm}} = 2.50$ Gy and $\Delta D_{\text{film},0.455\text{mm}} = 1.30$ Gy almost twice as high for the gel compared to the film.

4. Conclusion

Very small sized photon pencil beams down to about 0.455 mm lateral size can be visualized with MR-micro-imaging based polymer gel dosimetry not only in two dimensions at a certain depth with radiochromic films but continuously with 1 mm depth distance in 3-dimensions using a MR- μ -imaging insert to a high-field human scanner. The dosimetric resolution (voxel volume of $156 \times 156 \times 1000 \mu\text{m}^3$) is comparable to that of a commonly used radiochromic film and flatbed scanner system (pixel size of $169 \times 169 \mu\text{m}^2$). Quantitative data on absolute dose levels in the center of the small sized pencil beams might be influenced by edge enhancement and noise in the film scanner system.

5. References

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