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Stereotactic radiosurgery photon field profile dosimetry using conventional dosimeters and polymer gel dosimetry. Analysis and inter-comparison.

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Abstract. Small photon fields are increasingly used in modern radiotherapy and especially in IMRT and SRS/SRT treatments. Accurate beam profile measurements of such beams are crucial for a precise and effective treatment. In this work four different dosimetric methods have been used for profile measurements of three small 6 MV circular fields having diameters of 7.5, 15.0 and 30.0 mm. A small sensitive volume air ion chamber, a diamond detector, a novel silicon-diode array and Vinyl-Pyrrolidone based polymer gel dosimetry. The results of this work reveal the well-known disadvantages and/or problems of the conventional dosimeters for this kind of measurements and support that polymer gel dosimetry may overcome these problems. Conclusively, it is estimated that polymer gels could play an important role towards the minimization of the total SRS/SRT treatment error that is related with small field profile measurements.

1. Introduction

Narrow high-energy photon beams are increasingly used in modern radiotherapy (RT) and especially in Intensity Modulated RT (IMRT - beamlets) and Stereotactic Radiosurgery – RT (SRS/SRT) applications. Accurate measurements of the dose characteristics of such beams (percentage depth doses, beam profiles, output factors) are required as input to the Treatment Planning Systems in order to apply these modern RT techniques with high precision and in a trusted manner. Uncertainties related especially to profile measurements, result to certain clinical impact in 3D-CRT and in SRS/SRT.\textsuperscript{1,2} Broadening of the measured penumbra, usually an effect related to the size of the detector (volume averaging), result in over-irradiation of the adjacent Organs at Risk (OAR) since greater margins are needed to fully encompass the PTV.\textsuperscript{1} However, small photon beam measurements are
problematic because of the high dose gradients that are present and the non-existence of lateral electronic equilibrium. Moreover, the dosimeters used for such measurements should ideally exhibit certain characteristics such as dose-rate, directional and energy independence, tissue equivalency, high spatial resolution measurements, small sensitive volume, and without beam perturbation and positioning problems.

The aim of this work is to analyze and investigate the agreement between profile measurements of 6 MV circular SRS beams, provided by the BrainLab collimator system, performed using a PTW PinPoint ion chamber, a PTW diamond detector, a novel silicon diode array and polymer gel dosimetry. The whole process results to a better ‘knowledge’ of the true profiles.

2. Materials and methods

2.1 Source and the SRT system
All irradiations were performed using a Varian C600 Clinac 6 MV x-ray beam. The linear accelerator is adapted for stereotactic treatments via an additional tertiary collimator system by BrainLAB. The latter uses brass shelled lead collimators with a conical aperture of various sizes ranging from 7.5 to 35 mm.

2.2 Detectors
A linear diode array (DOSI) was fabricated on a single piece of high resistivity ($1-10$ k$\Omega$ cm) 300 $\mu$m thick n-type silicon by means of ion implantation. The diode pitch is 250 $\mu$m providing with sufficient resolving power for sub-millimetre measurements. The sensitive area of the device is 0.25x32 mm$^2$. For the DOSI measurements RW3 solid water slabs of various thickness were used.

A small waterproof diamond detector (type 60003 by PTW Freiburg) was also used. This is made from natural diamond with a sensitive volume of less than 6 mm$^3$, area between 3 and 15 mm$^2$ and thickness smaller than 0.4 mm (nominal value).

In addition, a small ionisation chamber specifically developed for small field dosimetry measurements (PinPoint 31014 by PTW Freiburg) has been used. It is waterproof and fully guarded, with a sensitive volume of 15 mm$^3$.

2.2.1 Polymer gels
The polymer gels prepared and used in this study were Normoxic – VinylPyrrolidone (VPL) based gels. The gel manufacturing process is described analytically in Papadakis et al.$^3$.

The calibration gel vials were irradiated to doses up to 25 Gy while the experimental gel vial was irradiated at 3 different sites, using 3 different SRS circular collimators: 7.5, 15.0 and 30.0 mm diameter, delivering 25 Gy at the depth of maximum dose ($d_{\text{max}}$) in each separate beam.

The irradiated gels were scanned with a 1.5 T Siemens Vision Plus MR Imager (Siemens medical Systems, Erlangen, Germany) using a slice selective 16-echo Carr-Purcell-Meiboom-Gill pulse sequence with an initial echo time of 40 ms with further 40 ms increments and a repetition time of 5 s. The slice thickness was selected to be 5 mm while the in-plane image resolution was 0.5 mm. This resolution size is directly related to the methods sensitive size (or ‘gel detector size’). The value of 0.5 mm is adequate for not introducing volume averaging effects. Nine signal acquisitions were performed resulting in a high SNR (~ 100) T2 map, derived using the imagers’ software.

2.2.1.1. Polymer gel data analysis
Central pixel: Within the T2-map (Figure 1), a pixel that corresponds to the beams’ central axis (central pixel) is firstly defined for each separate irradiation. This task was achieved by superimposing random iso-T2 lines on the irradiated area of the T2-map, and subsequently by fitting corresponding circles (Figure 2). The calculated centers of these circles were found to lie within, or to exist in the vicinity, of a unique pixel with dimensions 0.5 x 0.5 mm$^2$, the central pixel.

Profiles: As long as a linear dose-R2 response exists, the background subtracted spin-spin relaxation rate (R2net) profile along a line that intersects the central pixel, equals to the off-axis ratio of the studied irradiation area. The direction of the line can be arbitrary and profiles using a number of arbitrary lines can be averaged in order to reduce the statistical noise and derive a profile that
characterizes the whole beam. However, in order to use *all* the available gel data for the measurement of a profile that characterizes a certain small field (and not just a number of random line profiles passing through the central pixel), the following process can be followed: A large number of circles centered at the irradiated area’s central pixel can be used (three of them are presented in Figure 3 for the 30.0 mm collimator irradiated area). The average R²net value of the pixels that lie in the periphery of each separate circle (normalized to the central pixel R²net value) correspond to the off-axis ratio for a distance from the central axis equal to the circle radius. The normalization point in all cases is the mean value that correspond to the central pixel and its eight surrounding pixels.

3. Results and discussion
Polymer gel calibration test tubes measurement and analysis revealed that a linear dose – R² response exists (up to 25 Gy). Therefore, it can be stated that for the polymer gel batch produced and used in this study, relative R²net measurements equal relative dose measurements.

In Figure 3 are presented all the profile measurements performed in this study for the 7.5 mm, 15 mm and 30 mm collimator. The gel-data plotted uncertainties correspond to the standard deviation of the measurements used for each separate Off Axis Distance. The normalization point was at the beams’ central axis, for each separate beam. Polymer gels resulted in high spatial resolution and high spatial density dose measurements without positioning difficulties or electron transport alteration effects. Each gel data-point correspond to the mean value of all pixels lying on a circle with a radius equal to the Off Axis Distance while the profile measurements performed with the other dosimeters correspond to a random direction that is perpendicular to the central axis (and ideally intersects with it). A general satisfying agreement between datasets for each separate collimator is observed. However, it is easily observed that the PinPoint ion chamber broadens the measured penumbra. The diamond detector and the DOSI provides rather accurate results but they result to a slight pseudosharpening of the profiles possibly due to their high density. Moreover, for the 7.5 mm cone the diamond detector provides a rather underestimated FWHM. This effect is probably related with set-up errors that are very common in this kind of measurements.

In Table I are presented the 80-20 % penumbra widths of all the studied beams.

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**Figure 1:** T2-map of the experimental gel-vial irradiated using the 7.5, 15.0 and 30.0 mm collimators

**Figure 2:** Three separate random iso-T2 pixels superimposed on the T2-map (30.0 mm irradiated area – magnified). The centers of the fitted circles lie within or adjacent to a unique pixel: the central pixel. The mean value of the iso-T2 pixels that lie on a fitted circle correspond to the T2 value at an Off Axis Distance equal to the circles’ radius
Figure 3: Beam profiles of all studied small fields using all dosimetric techniques used in this study.

<table>
<thead>
<tr>
<th>Beam Diameter</th>
<th>Diamond</th>
<th>PinPoint</th>
<th>DOSI</th>
<th>Gel Dosimetry</th>
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</thead>
<tbody>
<tr>
<td>7.5 mm</td>
<td>1.5</td>
<td>2.5</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>15.0 mm</td>
<td>1.8</td>
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<td>1.9</td>
<td>2.1</td>
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<tr>
<td>30.0 mm</td>
<td>2.2</td>
<td>3.2</td>
<td>2.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The measured 80-20% penumbra widths of all the studied beams

4. Conclusions

The findings of this work support the argument that the detector size and composition together with positioning difficulties are the main problems related to small field file measurements. These problems can be addressed by the use of polymer gel dosimetry. Since small field profile measurement uncertainty contributes directly to the total treatment error, it is believed that polymer gels could have an important role towards the minimization of this error and therefore towards an improved clinical outcome of modern SRS/SRT treatments.

References