Gamma Knife relative dosimetry using VIP polymer gel and EBT radiochromic films.

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Abstract. The VIP polymer gel–MRI method and EBT Gafchromic films were employed to obtain relative dosimetry results for the Gamma Knife (GK) radiation fields of 4 mm and 18 mm nominal diameter. Results are compared to the corresponding calculations of GammaPlan Treatment Planning System (TPS) in the form of 1D profiles and 2D distributions. Measured and planned relative dosimetry datasets are found in close agreement within experimental uncertainties. A corresponding agreement is shown for Dose Volume Histogram (DVH) results that are available only through the application of the polymer gel method.

1. Introduction
The introduction of 3D conformal radiotherapy techniques - including Gamma Knife (GK) Stereotactic RadioSurgery (SRS) - into clinical practice, has stressed the importance of experimental verification of the complex dose distributions delivered. Currently, film dosimetry is a well-established method utilized to obtain experimental relative dosimetry data for commissioning and Quality Assurance (QA) purposes in such radiation therapy modalities. Polymer gel-MRI dosimetry studies have also been reported in the literature for SRS applications [1-8]. This work compares relative dosimetry results of the 4mm and 18mm GK radiation fields measured using a new normoxic gel dosimeter (VIP) [8] and a radiochromic film of improved dosimetric characteristics (EBT) [9], and exploits the inherent 3D dose integrating character of the polymer gel method to verify the planned Dose Volume Histogram (DVH) for each delivered dose distribution.
2. Materials and methods

The VIP gel dosimeter has already been successfully employed in SRS dosimetry [8]. Its composition (w/v: 8% NVP, 4% MBA, 7.5% gelatin, 0.0008% CuSO_4 and 0.007% ascorbic acid) comprises the result of an effort to maintain the wide dose response range of its “anoxic” predecessor (VIPAR [10]) while decreasing the lower limit of dose detection and simplifying its manufacturing procedure. Following preparation the gel solution was poured into two cylindrical glass vials of 95 mm height and 50 mm outer diameter that were hermetically sealed and stored overnight at room temperature to solidify. The first vial was employed in the GK irradiation while the second – to which a flexible, closed end catheter of 1.5mm external diameter was introduced through an appropriate hole drilled into its cap – was used for irradiation with a microSelectron 192Ir HDR remote afterloading unit for calibration purposes [10].

The phantom and experimental procedure followed for the GK irradiation is described in detail in a previous work [6] and ensures that the vial’s longitudinal axis is aligned to the z-axis of the unit. The GammaPlan Treatment Planning System (TPS) with the output factor values proposed by the vendor was utilized to plan and deliver the same dose of 30 Gy at two points along the z axis spaced 25 mm apart, employing the 4mm and 18mm helmet collimator respectively (see Fig. 1(a)). The calibration irradiation was performed on the same day by programming the mHDR-v2 192Ir source to deliver 10 Gy at 1 cm distance along the transverse source bisector in a single dwell position.

The readout of the two irradiated gel vials was performed 3 days post irradiation via Magnetic Resonance Imaging (MRI) on a 1.5 Tesla Philips Gyroscan NT MR scanner (Philips Medical Systems, Nederland BV), employing a volume selective, Carr-Purcell-Meiboom-Gill (CPMG), 18-echo pulse sequence (with an initial echo time (TE) of 40 ms, further 40 ms increments, and a repetition time (TR) of 2300 ms). A built-in quadrature radio-frequency (RF) body coil and a RF head coil were used for proton excitation and signal detection, respectively. The gel vials were placed at the center of the receiver coil in order to minimize RF field inhomogeneity effects. The acquisition and reconstruction inplane resolution was (0.54 x 0.54) mm², while the slice thickness was set to 0.75 mm resulting to a reconstructed voxel size of (0.54 x 0.54 x 0.75) mm³. This voxel size compromises the contradicting demands for submillimeter spatial dose-measurements resolution [11] and acceptable statistical noise.

After discarding the first echo image due to imperfections in the signal decay curve, a T2 map was calculated for each reconstructed axial (xy plane) slice using a mono-exponential fitting routine of pixel signal intensity versus echo time on a pixel by pixel basis. A 3D T2 matrix was then constructed for each vial by the acquired T2 maps and converted to the corresponding R2 (=1/T2) relaxation rate matrix that allows for the reconstruction of the scanned volume in any chosen oblique plane. Dose response data of the VIP polymer gel formulation were derived from the brachytherapy vial [10] and a linear fit was performed in the dose region of 2.5-33 Gy (R2 = (1.608±0.004)s⁻¹+(0.0820±0.0004) s⁻¹ Gy⁻¹ x D). For the GK vial, custom-written routines were utilized to determine the coordinates of the irradiation center of each delivered dose distribution, by exploiting the 3D symmetry of the GK radiation fields in space with respect to this point.

EBT radiochromic films have been introduced for radiotherapy dosimetry exhibiting high sensitivity and fine spatial resolution, without problems associated with energy dependence of response and water non-equivalence [9]. Two film sheets from the same batch were used; one for calibration and one for GK irradiation purposes. For the GK irradiation the same phantom and experimental procedure as with the VIP gel irradiation were employed. The gap for the accommodation of the gel vial was filled with two custom-made Plexiglas inserts and a (95 x 50) mm² film piece was aligned to the central coronal plane (xz plane) of the GK unit. Two single shots of 5 Gy maximum dose, spaced 35 mm apart were planned and delivered employing the 4 mm and the 18 mm helmet collimator respectively (see Fig. 1(b)). For calibration purposes, twenty two, (2.5 x 2.5) cm² precut EBT film pieces were irradiated using a Siemens Oncor 6 MV LINAC to deliver doses ranging from 10 to 2000 cGy. The films were placed perpendicular to the central axis of a (10 x 10) cm² collimated photon beam at 10 cm depth (SSD = 100 cm) in a solid water phantom of appropriate size to ensure full scatter conditions.
The scanning of all EBT films was performed 24 hours after irradiation to preclude postirradiation coloration effects, using a Microtek ScanWizard Pro (ScanMaker 9800XL) flatbed optical scanner in transmission mode. All films were placed in the same predetermined area of the scanner bed, maintaining the same orientation. 48-bit, RGB mode images were acquired with a resolution of 150 dpi (pixel size = 0.169 mm), and only the red color channel of the image was utilized and further processed. The mean pixel value (PV) of each calibration film piece was assigned to the corresponding delivered dose and a fifth degree polynomial fit was applied.

For the GK irradiated film, the aforementioned custom-written routines were used (in 2D) to determine the coordinates of the irradiation center of each delivered radiation field. Contrary to the 3D gel data, relative dosimetry results derived from the 2D film data are sensitive to potential misalignments of the film plane and the central coronal (xz) plane of the unit during irradiation (i.e. rotations about the x or z axes). The accuracy of the experimental procedure employed [6] however, ensures that no significant misalignment (i.e. capable of affecting relative dosimetry measurements) took place (see also Fig. 1(d) and 1(f)).

In order to obtain experimental, relative dosimetry results comparable to corresponding TPS calculations, a normalization of the measured data to the dose level at the irradiation center of each GK field is required. In an effort to suppress individual point uncertainties, this dose level was calculated by sampling a spherical volume (for gel data) or a circular surface (for film data) centered on the reference point using linear interpolation and estimating the mean dose value. The density of the interpolated points was similar to the corresponding grid of measurements, while the size of the sampled volume (or surface) was determined considering TPS calculations for the corresponding dose distribution in order to preclude averaging effects.

3. Results and Discussion

The planned distance between the two GK fields delivered to each dosimeter was verified within 0.3 mm (24.75±0.02 mm for the gel and 34.88±0.13 mm for the film; see also Fig. 1(c)-1(e)). In view of the GK unit spatial dose delivery accuracy (0.5 mm) this is an excellent agreement that negates any considerable misalignment of the film plane and the central coronal plane of the planned dose distributions during film irradiation.
Figure 2 presents the measured and TPS calculated relative dose profiles along the z-axis. The spatial coordinates of the irradiation center of each field were assigned to \((x,y,z) = (100,100,100)\) following the common GK unit convention. In this figure, gel results under 2.5 Gy (i.e. ~ 8.5\%) are not presented since this dose region lies below the method’s lower limit of detection, while gel measurements beyond \(z = 109\) mm are not available for the 18mm field since the vial’s length was not enough to accommodate the full delivered distribution (see figures 1(a) and 1(c)). Considering uncertainties attributed to single voxel (or pixel) results (i.e \(R_2\) or \(PV\)), an overall good matching of the three data sets is observed. It should also be noted that the TPS profiles are normalized to the dose level at the unit centre point (UCP), while experimental results are normalized to the dose level at the irradiation center of each field. According to the unit specifications, this should not deviate from the mechanical UCP more than 0.5 mm which can therefore be assumed as the maximum systematic uncertainty in the comparison between experimental results and TPS calculations.

Figures 3(a)-(b) present the comparison of measured and planned 2D relative dose distributions on the central coronal plane. In these figures, the TPS calculated and the corresponding experimental relative iso-dose lines are superimposed on the gel’s central coronal relative dose map. The observed deviation of measured and calculated data is attributed to the combined effect of experimental uncertainties - owing mainly to the uncertainty in the definition of the dose normalization level – and the total (geometrical and dose delivery) tolerances of the GK unit. Overall, the calculated and gel measured 2D relative dose sets present no systematic offsets and a distance-to-agreement better than 1 MR imaging pixel (0.5 mm). The same applies for film results, with the exception of a worse distance-
to-agreement (< 1 mm) observed for the 50% and the 60% relative dose levels at the 18mm field.

Figure 4 compares DVH values calculated by gel relative dosimetry results (sum of voxels to which relative dose values above a certain level are recorded) and corresponding TPS calculations for the GK fields involved in this work. For the 18mm field, experimental results and TPS calculations are in close agreement (better than 1.5%). Gel measurements for the 4mm field however, seem to systematically overestimate DVH values corresponding up to the 70% relative dose level. This is partially attributed to the uncertainty in the definition of the dose normalization level, which has a more pronounced effect on the 4mm helmet dose distribution due to its confined spatial extent. Small changes of this dose level, providing an acceptable distance-to-agreement between the measured and planned dose distribution, yield significant changes to the corresponding DVH results for the 4mm GK field (e.g. a 2% change of the dose normalization level results to a change of measured DVH values up to 5%). Moreover, the observed deviations between experimental and TPS calculated results (with the maximum being 6.5% for the 30% relative dose level) are practically comparable to the system tolerances considering the 0.5 mm spatial dose delivery accuracy that the vendor claims.

4. Conclusions

VIP polymer gel-MRI and EBT radiochromic film are of equal potential for 1D and 2D relative dosimetry in GK SRS applications. However, only polymer gel dosimetry can offer experimental dose verification in 3D, a feature that could justify the added effort and skill required by this method.

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References

[1] Ertl A, Berg A, Zehetmayer M and Frigo P. High-resolution dose profile studies based on MR imaging with polymer BANG™ gels in stereotactic radiation techniques. Magn. Reson. Imaging 18 343–9 (2000)
[2] Mack A, Scheib S G, Major J, Gianolini S, Pazmandi G, Feist H, Czempiel H and Kreiner H-J. Precision dosimetry for narrow photon beams used in radiosurgery-determination of Gamma Knife output factors. Med. Phys. 29 2080–9 (2002)
[3] Scheib S G, Schenkel Y and Gianolini S. Absolute dose verifications in small photon fields using BANG™ gel. 3rd Int. Conf. on Radiotherapy Gel Dosimetry J. Phys.: Conf. Series 3 228–31 (2004)
[4] Novotny J,Dvorak P, Spevacek V, Tintera J,Novotny J, Cechak T and Liscak R. Quality control of the stereotactic radiosurgery procedure with the polymer-gel dosimetry. Radiother. Oncol. 63 223–30 (2002)
[5] Scheib S G and Gianolini. Three-dimensional dose verification using BANG gel: a clinical example. J. Neurosurg. 97 582–7 S (2002)

[6] Karaiskos P, Petrokokkinos L, Tatsis E, Angelopoulos A, Baras P, Kozicki M, Papagiannis P, Rosiak J, Sakelliou L, Sandilos P, Vlachos L. Dose verification of single shot gamma knife applications using VIPAR polymer gel and MRI. Phys Med Biol 2005; 50:1235-50

[7] Papagiannis P, Karaiskos P, Kozicki M, Rosiak J, Sakelliou L, Sandilos P, Seimenis I, Torrens M. Three-dimensional dose verification of the clinical application of gamma knife stereotactic radiosurgery using polymer gel and MRI. Phys Med Biol 2005; 50:1979-90

[8] E. Pantelis, C. Antypas, L. Petrokokkinos, P. Karaiskos, P. Papagiannis, M. Kozicki, E. Georgiou, L. Sakelliou and I. Seimenis. Dosimetric characterization of CyberKnife radiosurgical photon beams using polymer gels. Med. Phys. 35, 2312-2320 (2008)

[9] M. Todorovic, M. Fischer, F. Cremers, E. Thom, and R. Schmidt. Evaluation of GafChromic EBT prototype B for external beam dose verification. Med. Phys. 33, 1321–1328 (2006)

[10] Kipouros P, Pappas E, Baras P, Hatzipanayoti D, Karaiskos P, Sakelliou L, Sandilos P, Seimenis I. Wide dynamic dose range of VIPAR polymer gel dosimetry. Phys. Med. Biol 2001; 46:2143-59

[11] A. Berg, M. Pernkopf, C. Waldhäusl, W. Schmidt, and E. Moser. High resolution MR based polymer dosimetry versus film densitometry: A systematic study based on the modulation transfer function approach. Phys. Med. Biol. 2004; 49:4087–4108