Assessment of radiochromic gel dosimeter based on Turnbull Blue dye for relative output factor measurements of the Leksell Gamma Knife® Perfexion™

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Abstract. The aim of the study was to perform assessment of radiochromic gel dosimeter based on Turnbull blue dye formed by irradiation (TB gel dosimeter) for measurement of ROFs for 4 mm and 8 mm collimators for the Leksell Gamma Knife Perfexion™. All measurements have been carried out using home-made spherical Perspex glass phantom of diameter 160 mm. TB gel dosimeters were scanned using homemade optical CT scanner. The results are compared with vendor recommended Monte Carlo calculated ROFs values of 0.814 and 0.900 for 4 mm and 8 mm collimators, respectively. The comparisons between the gel measurements and the treatment planning system (TPS) calculation are presented in the form of 2D isodoses for the central slices and 1D profile. Measured ROF 0.746 and 0.874 for 4 mm and 8 mm collimators respectively are in a reasonable agreement with vendor recommended values and measured relative dose distribution in a central slice and measured profiles of all shots show excellent correspondence with TPS.

1. Introduction
Radiochromic gel dosimeter based on Turnbull blue dye formed by irradiation (TB gel dosimeter) is an integral chemical dosimeter introduced by Solc et al. (2007). Basic properties of the TB gel dosimeter are summarized in Solc et al (2009). Upon irradiation the gel changes colour from yellow to green and blue because of the formation of Turnbull blue dye $K_3[Fe^{II}Fe^{III}(CN)_6]$, insoluble in water, which has a wide absorption peak with a maximum at a wavelength of approximately 690 nm. It offers several advantages such as inhibited diffusion, linear response from 0 Gy up to at least 400 Gy, easy preparation, non-sensitivity to oxygen and non-toxic composition. The response can be evaluated using both cone- and laser-beam optical CT. The main disadvantage is lower sensitivity and gel ageing caused by the spontaneous interactions of ferric ions with organic compounds resulting in the creation of Turnbull blue not originally initiated by ionizing radiation.
2. Material and Method

A TB gel was prepared according to preparation procedure suggested by Solc et al (2009) and is composed of a gel matrix - 0.25 % (w/w) phytagel, 0.5 mM potassium ferricyanide and 0.5 mM ferric chloride compound dissolved in 1mM sulphur acid medium. Phytagel was choose as a gelling agent for TB gel dosimeter since it exhibits the best dosimetric performance as was demonstrated in Solc et al (2010). Despite the higher amount of scattered light in phytagel, spontaneous reduction of Fe$^{3+}$ in gelatine makes phytagel the most suitable gelling agent. Prepared gel was poured into four glass cylindrical flasks (0.2 l, with diameter of 6 cm) available in our laboratory (plastic flasks could be also used) – three samples for irradiation and one sample as background. Gel dosimeters were stored in a refrigerator at 5°C. Solidification of TB gel took about 48 hours.

Irradiation was performed 48 hours after manufacturing on Leksell Gamma Knife (LGK) Perfexion$^{\text{TM}}$ (Elekta Instruments AB, Stockholm, Sweden) with the dose rate of 2.216 Gy/min at the date of irradiation. Gel dosimeters were fixed using special phantom designed by Semnicka (2013). The gel phantom made out of Perspex glass is designed in the shape of the standard spherical phantom of diameter 160 mm provided by the manufacturer and enables positioning of gel samples into various well defined positions (figure 1). Its purpose is therefore to map dose distributions that can then be compared with the calculations of the treatment planning system (TPS) (Leksell GammaPlan Version 10.1; Elekta Instruments AB, Stockholm, Sweden). Experiment was designed in the same way as was proposed by Moutsatsos et al (2009). Gel dosimeters were subsequently irradiated with one shot, 16 mm, 8 mm and 4 mm, positioned in the isocentre to a prescription dose of 55 Gy to 50% isodose. For planning TPS uses a cubic matrix of 31x31x31 grid points with variable grid spacing Dose distribution was exported with a slice thickness of 0.5 mm.

TB gel dosimeters were scanned using homemade optical CT scanner – 16-bit astronomy CCD camera (G2-0402 type, Moravian Instruments, Czech Republic), stepper motor (65535 micro-steps per one 360° turn), light source (a red diode array emitting light at a peak wavelength of 660 nm). Data analysis was performed with in-house code developed in Matlab$^{\text{®}}$ suggested by Solc et al (2009). The reconstructed image had resolution of 4.2 px/mm.

The TPS dose distributions were exported from Lekssel GammaPlan and imported into Matlab$^{\text{®}}$. Background map was determined from unirradiated gel sample and subtracted from each irradiated dosimeter. For each shot the central value was averaged from 25 pixels for the 16 mm shot, 15 pixels for the 8 mm shot, and 6 pixels for the 4 mm shot. The comparisons between the gel measurements and the TPS calculations are presented in the form of 2D isodoses for the central slices and 1D x profiles. Furthermore the relative output factors (ROF) for the 8 mm and 4 mm collimators which were defined in this study as the ratio of the dose rate in the unit centre point (Moutsatsos et al (2009)), were calculated using the following equation:

$$\text{ROF}_i = \frac{D_i}{t_i} \frac{D_{16}}{t_{16}}$$

(1)

$D_i$ is the dose delivered to the phantom center, and $t_i$ is the time necessary to deliver the dose $D_i$. The irradiation time $t_i$ for all collimators was taken from Leksell GammaPlan.
3. Results
The relative central x profiles for all shots are shown in figure 3 and the 2D relative dose distributions are shown in figure 4. The results of the ROF calculations are shown in Table 1. The table also summarizes vendor recommended values (Monte Carlo calculated) of 0.814 and 0.900 for 4 mm and 8 mm collimators, respectively. The discrepancy in the case of the 8 mm collimator was 2.9 % and in the case of the 4 mm collimator 8.4 %.

| Collimator | Number of pixels in ROI | Average CCD absorbance in ROI (± σ) | ROF<sub>TG</sub> | ROF<sub>LGP</sub> | Difference (%) |
|------------|------------------------|-------------------------------------|----------------|----------------|----------------|
| 16 mm      | 25                     | 194.1 (±0.9).10<sup>8</sup>          | -              | 1              | -              |
| 8 mm       | 15                     | 189.0 (±0.2).10<sup>8</sup>          | 0.874          | 0.900          | 2.9            |
| 4 mm       | 6                      | 178.9 (±0.1).10<sup>8</sup>          | 0.746          | 0.814          | 8.4            |

Table 1. Relative output factors measured by the TB gel dosimeter

4. Discussion
The measured relative dose profiles agreed perfectly with the TPS calculations, larger discrepancies were observed only in low dose region. For 16 mm collimator low dose region (below 20% isodose) was not possible to evaluate due to scatter artefacts from glass wall of flask. For 16 mm collimator using flasks with larger diameter or walls from non-scattering material would allow measurement in low dose region. Since TB gel is not sensitive to oxygen, it can be filled into plastic flasks as well. Replacing glass flasks by Teflon with refractive index close to gel would provide less distorted image, especially near the edge of the projection.
Figure 4. Comparison of 2D relative dose distributions. The red lines are Leksell GammaPlan calculations and the blue lines are gel measurements. Displayed isodoses: 10 (only for 4 and 8 mm collimators), 20, 40, 60, 80 and 100 %.

Measured ROF 0.874 and 0.746 for 8 mm and 4 mm collimator respectively are in a reasonable agreement with the TPS. The discrepancies are caused mainly by underestimated CCD intensities measured in the central part of 16 mm shot. Improved results would be obtained by using yellow light source (yellow diode array, emitting light at a peak wavelength of 590 nm) or delivering smaller dose to dosimeter. In case of 4 mm collimator dose response is averaged from a larger volume than it would be appropriate for the size of the 4 mm shot causing larger measurement error.

5. Conclusion
Measured relative dose distribution in central slice and measured profiles of all shots showed excellent correspondence with treatment planning system and makes TB gel dosimeter suitable for radiotherapy methods with steep dose gradients. Despite low sensitivity of the dosimeter, it appears to be a promising tool for three-dimensional dose measurements in high-dose-rate brachytherapy and stereotactic radiosurgery.

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7. References
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