Multi-dimensional dosimetric verification of stereotactic radiotherapy for uveal melanoma using radiochromic EBT film

Eva Sturtewagen1,2, Martina Fuß1, Leen Paelinck2, Carlos De Wagter2, Dietmar Georg1,*

1Division Medical Radiation Physics, Department of Radiotherapy, Medical University Vienna
2Division Radiotherapy and Nuclear Medicine, Ghent University Hospital

Received 2 March 2007; accepted 15 August 2007

Abstract
Since 1997, linac based stereotactic radiotherapy (SRT) of uveal melanoma has been continuously developed at the Department of Radiotherapy, Medical University Vienna. The aim of the present study was (i) to test a new type of radiochromic film (Gafchromic EBT) for dosimetric verification of class solutions for these treatments and (ii) to verify treatment plan acceptance criteria, which are based on gamma values statistics. An EPSON Expression 1680 Pro flat bed scanner was utilized for film reading. To establish a calibration curve, films were cut in squares of $2\times2\text{cm}^2$, positioned at 5 cm depth in a solid water phantom and were irradiated with different dose levels (0.5 and 5 Gy) in a $5\times5\text{cm}^2$ field at 6 MV. A previously developed solid phantom (polystyrene) was used with overall dimensions corresponding to an average human head. EBT films were placed at four different depths (10, 20, 25 and 30 mm) and all films were irradiated simultaneously. Four different treatment plans were verified that resemble typical clinical situations. These plans differed in irradiation technique (conformal mMLC or circular arc SRT) and in tumour size (PTV of 1 or 2.5 cm$^3$). Inhouse developed software was applied to calculate gamma ($\gamma$) index values and to perform several statistical operations (e.g. $\gamma$-area histograms). At depths of 10 mm $\gamma_{1\%}$ ($\gamma$-value where 1% of the points have an equal or higher value in the region of interest) were between 1–3 and maximum $\gamma_{>1}$ (% of $\gamma$-values $>1$ in the region of interest) areas were almost 30%. At larger depths, i.e. more close to the isocenter, $\gamma_{1\%}$ was $<1$ and $\gamma_{>1}$ areas were mostly $<5\%$. Average $\gamma$ values were about 0.5. Besides the compromised accuracy in the build-up region, previously defined IMRT acceptance criteria [Stock et al., Phys. Med. Biol. 50 (2005) 399-411] could be applied as well to SRT. Radiochromic EBT films, at larger depths, i.e. more close to the isocenter, $\gamma_{1\%}$ was $<1$ and $\gamma_{>1}$ areas were mostly $<5\%$. Average $\gamma$ values were about 0.5. Besides the compromised accuracy in the build-up region, previously defined IMRT acceptance criteria [Stock et al., Phys. Med. Biol. 50 (2005) 399-411] could be applied as well to SRT. Radiochromic EBT films, and the target volume (PTV of 1 or 2.5 cm$^3$), could be verified. These criteria were based on the gamma index ($\gamma$-value where 1% of the points have an equal or higher value in the region of interest) and maximum $\gamma_{>1}$ (% of $\gamma$-values $>1$ in the region of interest) areas. The gamma index values were calculated using inhouse developed software and were used to verify the treatment plans. The results showed that the treatment plans met the acceptance criteria for all depths and dose levels. The gamma index values were below 1 for most of the treatment plans, indicating good agreement between the computed and measured dose distributions.

Zusammenfassung
An der Klinik für Strahlentherapie der Medizinischen Universität Wien wurde 1997 die Stereotaktische Radiotherapie (SRT) von Aderhautmelanomen eingeführt und seither kontinuierlich weiterentwickelt. Das Ziel der vorliegenden Arbeit war, Bestrahlungspläne von Standardtherapiekonzepten für diese Therapie in mehreren Ebenen und mittels neuartiger Filme (Gafchromic EBT Film) zu verifizieren. Des Weiteren wurden Akzeptanzkriterien für Bestrahlungspläne angewendet und getestet, welche auf dem Gamma-Index beruhen. Für die Filmauswertung wurden ein EPSON Pro 1680 Flachbettscanner und eine Auswertesoftware (Eigenentwicklung) verwendet. Für die Bestimmung der Kalibrierungskurven wurden $2\times2\text{cm}^2$ große Filmstücke mit unterschiedlichen Dosiswerten (0.5 und 5 Gy) in 5 cm Tiefe in einem Festkörperphantom bestrahlt (6 MV, Feldgröße $5\times5\text{cm}^2$). Die dosimetrische Verifikation wurde in einem Festkörperphantom (Polystyrol) durchgeführt, welches in seinen Abmessungen einem durchschnittlichen menschlichen Kopf entspricht. Für jeden Bestrahlungsplan wurden vier Filme verwendet, die in unterschiedlichen Tiefen positioniert wurden. In Summe wurden vier typische klinische Situationen dosimetrisch verifiziert, die sich in der Größe des PTV (1 oder 2,5 cm$^3$) und in der Bestrahlungstechnik (mMLC geformte Stiefelder versus Pendelbestrahlung mit Rundkollimatoren) unterschieden. Zur Analyse von Bestrahlungsplänen wurden die $\gamma$-Index sowie daraus abgeleitete statistische
in combination with a flat-bed scanner, were found to be an ideal multidimensional dosimetric tool for treatment plan quality assurance. EBT films are a suitable and reliable dosimetric tool that could replace traditionally used radiographic films. The presented acceptance criteria for SRT treatment plans might be used as a benchmarking data-set for other stereotactic applications and/or other equipment (planning system and delivery hardware) combinations.

**Keywords:** Stereotactic radiotherapy, radiochromic film dosimetry, multidimensional dosimetry, uveal melanoma

### Introduction

Uveal melanomas are the most common primary ocular malignancies and tumour control with organ preservation is recognized as the most important goal of uveal melanoma treatments [1,2]. Depending on tumour size and location, there are several therapeutic options available, e.g. episcleral plaque brachytherapy or particle beam therapy e.g. [3–5]. Large uveal melanoma and those located at the posterior part of the eye represent typical irregular targets that can be treated stereotactically with high energy photon beams. In 1997 the Department of Radiotherapy, Medical University Vienna/Vienna General Hospital, started to treat uveal melanoma with linac based stereotactic radiotherapy (SRT). Although the standard external beam therapy for uveal melanoma remains proton beam therapy, the Vienna group developed an SRT treatment concept based on conformal mMLC treatments that are delivered in a computer controlled gated manner [6–8].

During the pre-clinical testing and development phase, dosimetric verification of this dedicated SRT application was rather cumbersome. Ionisation chamber measurements can be applied only to single points and the use of individually calibrated TLD positioned in multiple points has a limited spatial resolution. Although Gel dosimetry is a full 3D dosimetric approach and has been used for verification of ophthalmologic applications [9], it was out of scope for the present study for practical reasons. For multi-dimensional dosimetry standard radiographic film is a well established dosimeter. However, it has disadvantages such as limited dose range and increased sensitivity to low energy photons. Some of the problems related to radiographic film do not exist if radiochromic film is used. Their high spatial resolution, minor energy dependence, and near tissue equivalence make radiochromic film an alternative for dose distribution measurements in high energy photon beams. Recently a new type of radiochromic film became available. Its dosimetric properties have been determined [e.g.10–12] and it has been applied for verifying stereotactic body radiotherapy [13]. It was aimed to apply and test this new dosimetric media for multidimensional dosimetric verification of linac based SRT for uveal melanoma. Within this context previously derived acceptance criteria for the verification of IMRT plans, which were based on statistical evaluation of gamma (γ) values, were applied to benchmark SRT [14].

### Materials and methods

#### Film dosimetry

Radiochromic EBT film, launched by ISP (International Specialty Products, Wayne, NY) in 2004, was applied in...
all experiments. This film has two active layers, a sensitivity in the useful dose range between 0.01 and 8 Gy, absorption peaks at 633 and 585 nm and enables absolute dosimetry [10].

As film reading device the EPSON Expression 1680 Pro flat bed scanner was used. This scanner allows scanning in transmission mode with a maximum resolution of 3200 dpi and 48-bit colour depth. The maximum scanning area is A4 size and permits reproducible film positioning. For the present work, all scanned images were saved in a 48-bit TIFF-file and were further processed using MatLab (Version 6.5, Math Works Inc., Natwick, MA).

The working protocol used for this novel dosimetric system was newly established in cooperation between the Department of Radiotherapy, Medical University Vienna, and the Department of Radiotherapy and Nuclear Medicine, Ghent University. A brief summary of the scanning protocol and the film handling procedure is given in the Appendix A.

Prior to dose distribution measurements a calibration curve was established. EBT films were cut in squares of 2 × 2 cm² and positioned at 5 cm depth in a solid water phantom. To achieve sufficient backscatter, 15 cm of solid water was used. Films were irradiated in isocentric conditions, oriented perpendicular to the incident beam. Small EBT film pieces were centred in a 5 × 5 cm² field and doses between 0 and 500 cGy were delivered with a 6MV photon beam, in 9 steps of about 50 cGy. Absorbed dose determination was performed according to IAEA TRS 398 [15] with a calibrated Farmer chamber (PTW 30001) connected to a suitable electrometer. It is recommended to verify the calibration curve if a new box of films (even from the same batch) is used and especially if a new batch of films is used.

Uveal melanoma phantom

For dosimetric verification of linac based SRT of uveal melanoma a special phantom was developed in a previous study. It consists of tissue-equivalent slices of polystyrene (3 cm thickness, relative electron density = 1.03) and overall dimensions corresponding to an average human head. Some slabs of the phantom have dedicated inserts that can be exchanged in order to perform measurements with several dosimetric tools, such as films, TLDs or ionisation chambers. More specifically, the two upper slabs (each 3 cm thick) can be partly replaced by slices of smaller thickness (1 mm, 2 mm, 4 mm, 5 mm, 8 mm, 10 mm, 15 mm, 30 mm). These inserts allow dosimetry in coronal planes. This is the most practical direction, as the phantom is irradiated with its face upwards and the slices and films can be stacked up each other. An illustration of the uveal melanoma phantom is given in Fig. 1.

For the treatment plan verifications described below EBT films were placed at four different depths (10, 20, 25 and 30 mm) and all films were irradiated simultaneously. Taking into consideration that the isocentre was placed at 19 mm depth, these measurement depths cover the build-up region (depth 10 mm), a plane close to the isocentre (20 mm) and two more planes located deeper than the isocentric depth (25 and 30 mm) where typically a large dose gradient is present due to the location of critical structures such as the optical nerve [2].

For phantom positioning an infra-red reflective marker based system (ExacTrac ™, BrainLAB, Heimstetten, Germany) was utilized to minimize setup uncertainties.

Treatment plan categories

The uveal melanoma phantom was CT scanned (Siemens Somatom Plus S, Erlangen, Germany) with a slice thickness of 2 mm and the images (512 × 512 pixels, pixel size 0.45 mm²) were transferred to the treatment planning system (TPS) BrainSCAN (V5.21; BrainLAB, Heimstetten, Germany). Target volumes and critical organs (lens and optical nerves) were delineated on axial slices which resembled as closely as possible anatomical situations in typical uveal melanoma patients.

In total four typical treatment situations were simulated and different treatment plans were created, which differed in irradiation technique (conformal mMLC or circular arc) and in tumour size and shape (PTV of 1 cm³ or 2.5 cm³). For treatment planning the same goal as for patient treatments was applied, i.e. to fully encompass the PTV with the 80% isodose, while minimizing the dose to both optic nerve and lens [2,6,8]. A prescription dose of 5 Gy per fraction was chosen to ensure that the irradiation dose falls completely in the sensitivity range of EBT films. The prescribed dose for patient treatments is about twice as high [2].

All beam arrangements were based on a single isocenter and mimicking typical clinically applied treatments. For the treatment plans based on circular arc therapy six arcs were used. For circular arc treatments only a Clarkson integration algorithm could be applied in the commercial TPS for dose calculation. The static conformal mMLC-based irradiation technique was based on 9 beams and a beam’s eye view technique was applied for leaf setting. For mMLC based treatment a pencil-beam model was applied in the TPS [5]. For all calculations, the voxel size was set to 2 × 2 × 2 mm³. The TPS allowed extracting calculated doses as image or as a two- or three-dimensional matrix of dose values if the area of interest and the pixel size is specified.

Dosimetric comparison

The most commonly used approach for evaluating multi-dimensional dosimetric information, the gamma-evaluation method proposed by Low et al. [16], was used to
compare measured and calculated dose distributions using a 3% dose criterion (with respect to the prescribed dose) and 3 mm distance-to-agreement (DTA) criterion. For that purpose, the in-house developed software DosVer was utilized. Besides the gamma evaluation, DosVer calculates and displays the angle of the gamma vector and allows performing statistical operation with the gamma values, as well as evaluating dose profiles and dose difference maps [14].

For all comparisons a resolution of 50.8 dpi corresponding to 0.5 mm was used and adjusted through the scanner software. This resolution was a compromise; it provides enough details but does not require a too long calculation time and electronic data files are still manageable. The region of interest was selected in such a way that it did not contain the borders of the EBT film because borders were not suitable for dosimetry after cutting.

As mentioned above, for all treatment plans four films were placed at different depths. Thus the treatment plan verification procedure was not restricted to two dimensions and a simplified multi-dimensional evaluation was performed. However, with this 2.5 dimensional approach not every data point was examined as would be required in a full three dimensional approach. Because geometrical uncertainties in film positioning directly influence the results, several coronal dose planes were considered when exporting doses from the treatment planning system, i.e. the similarity between measured and calculated doses was checked separately for planes 1 mm beneath and 1 mm above the film plane. In the following only results are presented for those planes (out of the three evaluations at nominal depth ±1 mm) with the best agreement between calculated and measured doses.

Prior to any qualitative or quantitative evaluation of dosimetric information, the two data sets have to be registered. For the calculated dose distribution the isocentre is position is given in the export file of the TPS. On the measured dose distribution, the isocentre was marked with lines (according to room lasers) that were drawn on the film positioned in the isocenter. On the other films, the projected position of the isocenter was given by the dimensions of the phantom slabs or spacers. For film orientation in the verification software physical borders of the films were used as geometrical landmarks, e.g. to perform rotations. In order to correct for experimental uncertainties the exported dose matrix from the TPS at the isocentric plane was re-adjusted as follows. In a first step, the theoretical isocentric position in longitudinal (X-direction) and lateral directions (Y-direction) was looked up and then dose profiles in two orthogonal directions (X and Y) were compared for both calculated and measured dose distributions. By doing so the position of the film-isocentre was defined as the position that gives the best agreement between calculated and measured dose profiles. On average the extra adjustment of the isocentric position was 2 pixels (both in X and Y direction), which means the average spatial shift was about 1 mm.

As a first assumption, it was decided to use the treatment plan acceptance criteria determined in the department in Vienna for Intensity Modulated Radiotherapy (IMRT) treatment plans [14]. Table 1 summarizes the criteria, which are based on gamma values, i.e. \( \gamma > 1 \) (percentage of
gamma-values that is > 1 in the region of interest), \(\gamma_{\text{mean}}\) (average gamma value in the region of interest) and \(\gamma_{1\%}\) (gamma-value where 1% of the points have an equal or higher \(\gamma\)-value in the region of interest). It must be emphasised that (i) these criteria were determined from patient specific treatment plan QA for IMRT in axial planes close to the isocenter and (ii) that these criteria are equipment specific, i.e. they will depend on the treatment planning system and on delivery equipment. In the present work they are applied to stereotactic treatments for benchmarking these treatments.

**Results**

**Film dosimetry**

For the analysis net pixel values, which were derived from film scanning, were directly used for further processing. This procedure is equivalent to the traditional method of using optical densities to convert film reading into dose values. Figure 2 shows the calibration curve applied. Contrary to other reports, we used the green colour channel of the scanner for EBT film dosimetry. This channel showed superior results in terms of read-out reproducibility and smallest deviations between measured data points and the calculated points using an analytical fit function.

**mMLC based treatment plans**

Case 1-Small tumour: Table 2 summarizes results for the 3 previously defined statistical parameters, \(\gamma_{1\%}\), \(\gamma_{\text{mean}}\) and \(\gamma_{>1}\). The data show high accuracy at planes located at 20, 25 and 30 mm depth, respectively. At a depth of 10 mm which is located in the build-up region, both \(\gamma_{1\%}\) and \(\gamma_{>1}\) values were higher although the mean gamma values were reasonable. When analysing results at 10 mm depth in more detail (see Fig. 3a), maximum \(\gamma\)-values were > 2, with \(\gamma_{\text{max}} = 3.46\). When also examining the \(\gamma\)-angle (see Fig. 3b), it becomes obvious that the high \(\gamma\)-values are mainly caused by the dose difference and not by geometric uncertainties. The dose measured by the films was on average 0.12 Gy higher than the calculated one (maximum dose: 2.6 Gy at that depth).

Although for 20, 25 and 30 mm depths the evaluated parameters illustrate high accuracy, further investigations were performed by looking at dose profiles. This comparison indicated that the measured dose gradient was less steep compared to the calculated one and small dosimetric deviations were observed, i.e. in the isocentre the measured dose was lower while in the penumbra region the measured dose was higher than the calculated one.

Case 2-Large tumour: The results for the three gamma-evaluation parameters are summarized in Table 3. The data show again that there was good agreement between calculated and measured dose distributions, especially at 20, 25 and 30 mm depth. In general the parameters were similar to the ones for the treatment with the small tumour. At 10 mm depth, \(\gamma_{1\%}\) was 1.7, which again indicated impaired dosimetric accuracy in the build-up region. As for the other case based on the mMLC treatment, the measured dose was higher than the calculated one. In the region of interest, the measured dose was on average 0.06 Gy higher than the calculated dose (maximum dose: 3.7 Gy at that depth).

**Arc therapy**

Case 3-Small tumour: Table 4 presents results for all four verification depths. The resulting evaluation parameters all confirm that a high accuracy was reached.

---

**Table 1**

<table>
<thead>
<tr>
<th>Value</th>
<th>Range</th>
<th>Appraisal and approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_{1%})</td>
<td>0–1.5</td>
<td>High accuracy: no further investigation</td>
</tr>
<tr>
<td></td>
<td>1.5–2</td>
<td>Limited accuracy: other verification tools such as angle distribution, dose difference map, profiles are applied for further evaluation</td>
</tr>
<tr>
<td></td>
<td>&gt; 2</td>
<td>Low accuracy: measurement has to be repeated to exclude possible experimental influences; further investigation necessary</td>
</tr>
<tr>
<td>(\gamma_{\text{mean}})</td>
<td>0–0.5</td>
<td>High accuracy: no further investigation</td>
</tr>
<tr>
<td></td>
<td>0.5–0.6</td>
<td>Limited accuracy: other verification tools such as angle distribution, dose difference map, profiles are applied for further evaluation</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.6</td>
<td>Low accuracy: measurement has to be repeated to exclude possible experimental influences, further investigation necessary</td>
</tr>
<tr>
<td>(\gamma_{&gt;1})</td>
<td>0–5%</td>
<td>High accuracy: no further investigation</td>
</tr>
<tr>
<td></td>
<td>5–10%</td>
<td>Limited accuracy: other verification tools such as angle distribution, dose difference map, profiles are applied for further evaluation</td>
</tr>
<tr>
<td></td>
<td>&gt; 10%</td>
<td>Low accuracy: measurement has to be repeated to exclude possible experimental influences, further investigation necessary</td>
</tr>
</tbody>
</table>
For this verification case the depths of the calculated dose distributions were slightly changed at nominal depths of 20 and 25 mm, i.e. exported dose matrixes differed by 0.7 mm from this nominal value. By doing so the gamma evaluation principle was “manually” extended to a 3-dimensional method. Such procedures, however, did not improve the results presented in Tables 3 and 4 for case 1 and 2 based on mMLC beam delivery.

Case 4-Large tumour: Table 5 summarizes γ-parameters. Compared to the other test cases 1–3, the agreement between measured and calculated dose distributions was limited not only at 10 mm depth but also at 30 mm. From the γ-index values and by looking at dose profiles it was observed that the shape of the isodose distribution was somewhat different. For that reason the γ-value at 10 mm depth was exceeding unity for almost one third of the region of interest. In general, at all depths the agreement was lowest for test case 4, with the highest average γ-values and the largest number of pixels exceeding the γ-criteria.

Additional experiments

As the results for case 4 were the least accurate, additional experiments were performed for the circular arc cases. Films were placed at six depths (4, 7, 9, 11, 20 and 30 mm) in the uveal melanoma verification phantom and the same treatment plans were delivered. Basically very similar results were obtained compared to the results presented above in Tables 3 and 4, with the largest deviations in the build up region for the large tumour at shallow and at large depth. The maximum γ1% at shallow depths was around 1.7 and maximum γ > 1 regions were up to 15% of the total ROI.

Discussion

In general, results of the dosimetric comparison between measured and calculated 2-dimensional distributions demonstrate a high level of agreement. However, especially in the build-up region and for circular arc treatments the accuracy was reduced. There are several factors that might explain these inaccuracies and/or inconsistencies.

In the present study a 2D measurement was performed for dosimetric verification of 3D dose distributions. In order to find the best agreement between measured and calculated dose distributions a simple manual optimization procedure was performed, i.e. the γ-evaluation was extended from 2-D to quasi 3-D by manually adjusting the calculation plane and the measurements plane. Such a simple dose calculation plane optimization already improved the verification results significantly. The extension
of the 2-D gamma evaluation procedure could be further automated in the in-house developed software DosVer to a full 3-D method where the EBT films are still placed only in one plane, but they are point by point compared with the calculated dose distributions in three dimensions. Another alternative is to pile up EBT films in order to obtain a quasi 3-D dosimetric tool with a resolution of 0.234 mm perpendicular to the film planes. EBT film is an expensive dosimeter and for the present work such an approach was out of scope for economic reasons.

Treatment planning systems have compromised accuracy in the build-up region with a rather high dose gradient and it has been suggested to use less strict tolerance criteria in this region compared to high dose and
low dose gradient regions [17]. In that respect it must be emphasized that we used the same acceptance criteria for all depths for better comparison with previous experience from patient specific QA in IMRT. These items are clearly reflected in the presented results, where for three out of four treatment plans results at 10 mm depths were not as accurate as for isocentric depths. Furthermore, dose calculations for circular arc treatment were limited to a simple Clarkson integration algorithm while for the conformal mMLC treatment a pencil beam algorithm was available in the TPS. The latter algorithm is more complex resulting in more exact calculations. For that reason it is understandable that the results for the circular arc treatments were less accurate (e.g. at 30 mm depth).

Dose calculations for very small fields, which are constantly used in stereotactic radiotherapy, are directly influenced by basic beam parameters which are in turn more difficult to measure with a high accuracy. Finally, dose calculation models do not provide the same level of accuracy for all clinical situations. A well-known fact concerning computerized dose calculations is that in practice some sort of “priority-compromise” needs to be found between speed and accuracy. Unfortunately, uncertainties are not accounted for in an open and sincere manner, even though they are inevitable when aiming to model complex processes such as dose deposition in a patient. In that aspect the importance of presenting also flaws and weaknesses of a dose calculations model by the companies that market TPS’s must be emphasized. Such issues are often discussed in a scientific context, but probably not as frequently in the clinical routine work.

Another source of error, besides calculation inaccuracies, is experimental uncertainties of film dosimetry. The most likely inaccuracy is a small but unavoidable thin layer of air between film sheets and the phantom slabs, which is well known to disturb experimental film dosimetry [18]. Additionally, small inaccuracies in the positioning of single or multiple film sheets are likely to happen, for example (sub-)millimetre shifts when placing films in between the phantom slabs or small variations in outer film sheet dimensions [19]. Such geometric influences might have even a larger contribution in the two last circular arc experiments where several film sheets were placed very close to each other and only thin phantom slabs were used. Although a tape around the total phantom was used to put extra pressure on the phantom slabs and the films the pressure was not high enough to avoid air gaps completely. In that aspect only a reconstruction of the phantom, e.g. with integrated clamps would help to overcome this problem.

The characteristics and some clinical applications of radiochromic EBT films have been described in recent publications [10–13,20–22]. With a dedicated protocol based on repeated film evaluation, i.e. identical films are read five times in succession without moving it on the scanner bed, to reduce the impact of scanner noise, a 2.5% accuracy has been reported [10]. If bad pixels were removed the one sigma uncertainty was even lower than 2% for doses above 0.4 Gy. Since a similar procedure with sufficient scanner warm-up and multiple scanning/reading of the same film without repositioning was applied in the present study the dosimetric uncertainty was below 3%. As radiochromic EBT can be considered as tissue equivalent, the attenuation due to parallel irradiation can be neglected [22,23].

For this study the chosen plan evaluation criteria were derived from acceptance criteria for patient specific IMRT verification [14]. In a first attempt these criteria were extrapolated to a very special stereotactic treatment, based on different hardware for beam delivery, a different TPS and different dosimetric tools, i.e. EBT films. In an ongoing project more stereotactic indications are verified in a similar manner in order to amend this first series of

---

### Table 3
Summary of gamma evaluation parameters for the conformal mMLC plan with large tumour (Values in bold: low or limited accuracy according to Table 1).

<table>
<thead>
<tr>
<th>Depth of dose comparison</th>
<th>$\gamma_{1%}$</th>
<th>$\gamma_{mean}$</th>
<th>$\gamma_{&gt;1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>1.70</td>
<td>0.27</td>
<td>2.17%</td>
</tr>
<tr>
<td>20 mm</td>
<td>0.70</td>
<td>0.29</td>
<td>0.04%</td>
</tr>
<tr>
<td>25 mm</td>
<td>0.80</td>
<td>0.27</td>
<td>0.07%</td>
</tr>
<tr>
<td>30 mm</td>
<td>0.75</td>
<td>0.25</td>
<td>0.27%</td>
</tr>
</tbody>
</table>

### Table 4
Summary of gamma evaluation parameters for the circular arc plan with small tumour.

<table>
<thead>
<tr>
<th>Depth of dose comparison</th>
<th>$\gamma_{1%}$</th>
<th>$\gamma_{mean}$</th>
<th>$\gamma_{&gt;1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>0.95</td>
<td>0.40</td>
<td>0.91%</td>
</tr>
<tr>
<td>20.7 mm</td>
<td>1.12</td>
<td>0.34</td>
<td>2.15%</td>
</tr>
<tr>
<td>24.3 mm</td>
<td>0.85</td>
<td>0.30</td>
<td>0.43%</td>
</tr>
<tr>
<td>30 mm</td>
<td>0.95</td>
<td>0.25</td>
<td>0.20%</td>
</tr>
</tbody>
</table>

### Table 5
Summary of gamma evaluation parameters for the circular arc plan with large tumour (Values in bold: low or limited accuracy according to Table 1).

<table>
<thead>
<tr>
<th>Depth of dose comparison</th>
<th>$\gamma_{1%}$</th>
<th>$\gamma_{mean}$</th>
<th>$\gamma_{&gt;1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>1.40</td>
<td>0.76</td>
<td>28.67%</td>
</tr>
<tr>
<td>20 mm</td>
<td>1.10</td>
<td>0.31</td>
<td>1.45%</td>
</tr>
<tr>
<td>25.6 mm</td>
<td>1.18</td>
<td>0.44</td>
<td>4.30%</td>
</tr>
<tr>
<td>30.6 mm</td>
<td>1.22</td>
<td>0.54</td>
<td>5.20%</td>
</tr>
</tbody>
</table>
experiments and to be able to define suitable acceptance criteria for multidimensional verification of stereotactic treatments.

**Conclusion**

Radiochromic EBT films, in combination with a suitable film reading device were found to be an ideal dosimetric tool for quality assurance, for example to verify a class solution as done in the present work. Moreover, EBT films are a suitable, reliable dosimetric tool that could replace traditionally used radiographic films in the near future.

For the stereotactic application dose calculation accuracy in the build-up region was limited and the tolerance criteria in this region need to be relaxed compared to high dose and low dose gradient regions close to the isocenter.

At depth > 20 mm the agreement between EBT film measurements and dose calculations was found to be comparable to other precision radiotherapy techniques such as IMRT. As expected, results obtained with a pencil beam calculations were in general better than the one obtained with Clarkson integration. The acceptance criteria based on the dosimetric and geometric accuracies achieved within the present study could be used as a benchmarking data-set for verifying other stereotactic applications or commission different SRT equipment (TPS, delivery hardware) combinations.

**Appendix A**

Table A1.

<table>
<thead>
<tr>
<th>EPSON scanner protocol</th>
<th>EBT Gafchromic film protocol</th>
<th>Film calibration protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use a positioning frame to position the films on the same place</td>
<td>Use gloves to handle the films</td>
<td>Use gloves to handle the films</td>
</tr>
<tr>
<td>Remove the positioning frame during scanning</td>
<td>Use tight-light envelopes for storage</td>
<td>Position films at reference position (parallel or perpendicular) at 5 or 10 cm depth</td>
</tr>
<tr>
<td>Perform minimum 5 successive scans before real measurements</td>
<td>Cut film pieces minimum one day prior to irradiation</td>
<td>Irradiate film</td>
</tr>
<tr>
<td>Turn the scanner off between the measurements</td>
<td>Use the films in portrait orientation</td>
<td>Repeat previous steps for about 8 different dose levels in the dose range between 0.2 and 8 Gy</td>
</tr>
<tr>
<td>Use the same specifications in the EPSON software: professional mode, transparent document type, set 48-bit, colour correction off; select 150 dpi resolution</td>
<td>Scan the films before and after irradiation and use the net optical density for dosimetric evaluation</td>
<td>Perform absolute dosimetry at the position of film, for the same number of monitor units that were used for film exposure.</td>
</tr>
<tr>
<td></td>
<td>After irradiation wait at least 4 hours to scan the films</td>
<td>Determine film calibration curve using</td>
</tr>
<tr>
<td></td>
<td>Use/select the green colour channel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Use MatLab software to obtain and process the measured pixel-values</td>
<td></td>
</tr>
</tbody>
</table>
References


