Feasibility of polymer gel-based measurements of radiation isocenter accuracy in magnetic fields

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Abstract

For conventional irradiation devices, the radiation isocenter accuracy is determined by star shot measurements on films. In magnetic resonance (MR)-guided radiotherapy devices, the results of this test may be altered by the magnetic field and the need to align the radiation and imaging isocenter may require a modification of measurement procedures. Polymer dosimetry gels (PG) may offer a way to perform both, the radiation and imaging isocenter test, however, first it has to be shown that PG reveal results comparable to the conventionally applied films. Therefore, star shot measurements were performed at a linear accelerator using PG as well as radiochromic films. PG were evaluated using MR imaging and the isocircle radius and the distance between the isocircle center and the room isocenter were determined. Two different types of experiments were performed: i) a standard star-shot isocenter test and (ii) a star shot, where the detectors were placed between the pole shoes of an experimental electro magnet operated either at 0 T or 1 T. For the standard star shot, PG evaluation was independent of the time delay after irradiation (1 h, 24 h, 48 h and 216 h) and the results were comparable to those of film measurements. Within the electro magnet, the isocircle radius increased from 0.39 ± 0.01 mm to 1.37 ± 0.01 mm for the film and from 0.44 ± 0.02 mm to 0.97 ± 0.02 mm for the PG-measurements, respectively. The isocenter distance was essentially dependent on the alignment of the magnet to the isocenter and was between 0.12 ± 0.02 mm and 0.82 ± 0.02 mm. The study demonstrates that evaluation of the PG directly after irradiation is feasible, if only geometrical parameters are of interest. This allows using PG for star shot measurements to evaluate the radiation isocenter accuracy with comparable accuracy as with radiochromic films.

1. Introduction

The integration of magnetic resonance imaging (MRI) into radiation devices such as linear accelerators (linac) or \(^{60}\)Co-based systems, for MR-guided radiotherapy (MRgRT) (Lagendijk et al 2008, Fallone et al 2009, Keall et al 2014, Mutic 2014) is expected to allow for a better adaption of the dose distribution to anatomical changes due to the excellent soft-tissue contrast of MR images (Reiser et al 2018) as compared to image-guided procedures with x-rays in conventional radiotherapy. In contrast to x-rays, MRI does not involve exposure to ionizing radiation (Dirix et al 2014) and therefore allows repeated use, e.g. for online gating of moving targets (Heerkens et al 2014) or real time plan adaption (Kontaxis et al 2017). On the other hand, the static magnetic field will affect the trajectory of secondary electrons, which will result in a change of the dose distribution relative to that without magnetic field (Reiffel et al 2000, Raaymakers et al 2004, Raaijmakers et al 2007a, 2007b, Kirkby et al 2008, Oborn et al 2009). In addition, the response of dose measuring devices, such as ionization chambers, is affected by the magnetic field as demonstrated by several studies (Meijwing et al 2009, Reynolds et al 2013, Smit et al 2013, Spindeldreier et al 2017). As a consequence, additional quality assurance measures have to be developed for these new devices.
As for many other high-precision radiotherapy techniques, the accuracy of the radiation isocenter is of central importance. For linac-based radiosurgery, the Winston–Lutz test (Lutz et al 1988) or simple star shot measurements (Treuer et al 2000) on radiographic or radiochromic films have been used for this purpose (Depuydt et al 2012). In MRgRT-devices, however, the deflection of secondary electrons by the magnetic field may lead to an asymmetric beam profile (Raaijmakers et al 2008). As a consequence, altered test results are expected, which in contrast to application in radiosurgery, cannot be attributed to solely mechanical machine inaccuracies. Thus the interpretation of the test results also has to be reconsidered. To compensate for the effect of the magnetic field, attaching high density material directly to the radiochromic films to reduce the range of the secondary electrons has been suggested (van Zijp et al 2016). As treatment plans in MRgRT are intended to be adapted based on MR-images, it is important to check not only the radiation, but also the imaging isocenter. This requirement is similar to that of combined imaging devices like positron emission and MR tomography (PET-MR), where the alignment of both imaging isocenters is always assumed (Judenhöfer et al 2007, 2008). In MRgRT-devices, the radiation and imaging isocenter should ideally be checked simultaneously in a single measurement. For this purpose, polymer dosimetry gel (PG) could be used in the future as it can also be visualized in MRI.

After irradiation, PG polymerizes locally and alters the relaxation rate $R_2$ of the transverse magnetization in MRI depending on the locally absorbed radiation dose (Baldock et al 2010). Recently, it has been shown, that 3D-polymer gel dosimeters are a useful tool to verify motion compensation concepts in photon radiotherapy (Mann et al 2017) and to capture and resolve steep dose gradients in MRgRT (Roed et al 2017). Also other types of 3D gels were recently investigated in magnetic fields (Lee et al 2017a, 2018, Mein et al 2017) and only minimal $B_0$-field effects were found (Lee et al 2017b). Up to now, however, the possibility of measuring the accuracy of the radiation and imaging isocenter has not been investigated.

As a first step into this direction, this study investigates whether PG can be used to determine the radiation isocenter via star shot measurements. Feasibility of such measurements is not evident as the handling of dosimetry gels encounters several difficulties: the sensitivity of the response to oxygen contaminations (De Deene et al 2006), temperature and evaluation time after irradiation, which is usually 48 h (Mann et al 2017). Without this time delay, it is especially impossible to perform absolute dose measurements due to large variations of the dose versus the $R_2$ calibration curve (Vandecasteele and De Deene 2013a). In this study, we therefore focus on geometrical aspects rather than quantitative dose evaluation and investigate whether the MR-evaluation can be performed directly after irradiation. In addition, we investigate whether PG and film measurements provide comparable results.

2. Material and methods

2.1. Experimental setup

In this study, the geometrical information on radiation isocenter accuracy obtained from PG measurements was compared with that obtained by radiochromic films (EBT3, ISP, Wayne, USA). For this, two types of experiments were performed: (i) to test the feasibility of PG for star shot measurements, the gel was poured into spherical flasks composed of borosilicate glass (outer diameter = 8.5 cm, volume = 250 ml, wall thickness = 1 mm). (ii) To compare the results of star shot measurements with and without external magnetic field, petri dishes composed of soda-lime glass (outer diameter = 10 cm, height = 2 cm, volume = 100 ml, wall thickness = 1 mm) were used as a gel container. The small height was necessary as the employed portable experimental electro magnet (AGEM 5520, Schwarzbeck Mess-Elektronik, Schönau, Germany, output of the power supply: 250V/20A) allowed only for pole shoe distances of up to 3.5 cm, if a maximum magnetic field strength of 1 T is to be obtained. All irradiations were performed with a clinical linac (Artiste, Siemens Healthineers, Erlangen, Germany).

2.1.1. Polymer gel

Polymer gel measurements were performed using the PAGAT (PolyAcrylamide Gelatin gel fabricated at ATMospheric conditions) polymer gel. The gel consists of two different monomers (3% w/w acrylamide and 3% w/w N,N’-methylene-bis-acrylamide) as active components embedded within a gelatin matrix (6% w/w Gelatin, 300 bloom, SIGMA Aldrich). To minimize the influence of dissolved oxygen, 5 mM bis[tetakis(hydroxymethyl) phosphonium] chloride (THPC) was added as an antioxidant. To further reduce the amount of dissolved oxygen, the gel was additionally flushed with nitrogen for 3 min directly before adding the antioxidant (De Deene et al 2002). A detailed description of the production procedure of the PG can be found elsewhere (De Deene 2006). After also flushing the containers with nitrogen, they were filled with PG. The containers were then enwrapped in aluminum foil and placed in a desicator, which was entirely flushed with nitrogen, and stored in a refrigerator at 4 °C for 20–24 h. The gels were removed from the refrigerator 4 h before irradiation and stored at room temperature.

http://schwarzbeck.de/Datenblatt/k5520.pdf last checked: 30 April 2018.
2.2. Measurements

2.2.1. Feasibility of polymer gel for star shot measurements

At our institution, the standard protocol for checking the isocenter accuracy for gantry rotations is a star shot measurement using a $40 \times 0.4$ cm$^2$ field. This field is irradiated under nine equidistant gantry angles ($20^\circ$, $60^\circ$, $100^\circ$, $140^\circ$, $180^\circ$, $220^\circ$, $260^\circ$, $300^\circ$ and $340^\circ$) using 300 MU/angle and a dose rate of 300 MU min$^{-1}$. Gafchromic EBT3 films (size $11 \times 10$ cm$^2$) were irradiated between two 1 cm slabs of water-equivalent material (RW3, PTW Freiburg, Germany) after marking the isocenter as defined by the in-room laser system (LAP GmbH Laser Applikationen, Lüneburg, Germany). For PG measurements, the spherical flask was positioned at the isocenter by means of three MR-visible markers (Beekley Medical, Bristol, USA) on the surface of the container. The same irradiation procedure as used for films was performed.

2.2.2. Star shot measurements with and without magnetic field

To investigate the isocenter accuracy for gantry rotations, the center of the electromagnet (figure 1(a)) was positioned at the isocenter with the magnetic field oriented parallel to the gantry axis ($Y_f$ according to (IEC 2011)) as shown in (figure 1(c)). Due to its weight (120 kg), the magnet had to be positioned by means of a special lifting cart (SPS/SPF, Hanse Lifter, Bremen, Germany), which limited the position accuracy to $\pm 0.5$ mm. To allow for accurate and reproducible positioning of the petri dishes and the films inside the magnet a dedicated holder was 3D printed using the VeroClear material (RDG810, Stratasys, Eden Prairie, USA, density: $1.18\text{–}1.19$ g $\text{cm}^{-3}$) and this holder was clamped between the pole shoes of the magnet (figures 1(a) and (b)). PMMA-plates for films and a printed mounting ring for the gel containers (figure 1(d)) can then be inserted into the holder. In this way, the PG and the film had a fixed spatial relation relative to the magnet. The positions of the room lasers were marked on both the film and the PG container using a MR-visible marker in the latter case. The star shot experiment was then performed either with or without a magnetic field of 1 T for both the PG and film resulting in a total of four measurements.

Due to the experimental setup, a slightly different irradiation protocol was followed as compared to the standard star shot procedure (section 2.2.1): (i) to avoid scattering caused by the magnet coils, a 5 mm circular collimator was used instead of a slit-field. (ii) The star shot was performed with five rather than nine beams (gantry angle $0^\circ$, $72^\circ$, $144^\circ$, $216^\circ$, $288^\circ$). As a result, the overlap of the beams at the isocenter is reduced allowing for a better investigation of the deformed beam profile in the presence of high magnetic fields. (iii) Due to the lifting cart the gantry rotation was limited to angles between $260^\circ$ and $80^\circ$. To obtain a comparable beam arrangement as for the standard star shot measurements without the electromagnet (section 2.2.1), the irradiation was performed in two steps: after irradiating the upper hemisphere (gantry angles of $288^\circ$, $0^\circ$ and $72^\circ$), the gel containers and films were rotated by $180^\circ$ around the axis of the magnet to mimic an irradiation from the lower hemisphere (corresponding to gantry angles $216^\circ$ and $144^\circ$). This procedure resulted in a complete star shot with equidistant beams with angular distances of $72^\circ$ between two adjacent beams. Inaccuracies which may have been introduced by this procedure are discussed below. (iv) To avoid overheating the magnet (a field strength of 1 T requires a coil current of 12 A), the operation time was kept to a minimum by using the flattening filter free mode of the linac at a dose rate of 2000 MU min$^{-1}$ with a total of 500 MU/beam.

2.3. Evaluation

All films were scanned in the same orientation with an Epson 1000XL flatbed scanner (Epson Seiko Corporation, Nagano, Japan) with a resolution of 150 dpi. The laser isocenter was reconstructed by means of the marks on the film.

The PG containers were scanned on a 3 T Biograph mMR (Siemens Healthineers, Erlangen, Germany) inside a 16-channel head/neck coil using a multi-spin-echo sequence as implemented by the vendor with 32 equidistant echoes and a bandwidth (BW) of $130$ Hz/pixel. For the standard star shot without the electromagnet (section 2.2.1), the irradiated gel container was scanned 1 h, 24 h, 48 h and 216 h after the irradiation using the following imaging parameters: Repetition time $TR = 5000$ ms, echo time $TE = 30.0$–$960.0$ ms with an equidistant echo spacing of 30 ms, resolution $= 0.5 \times 0.5$ mm$^2$, employing a single slice with a thickness of 5 mm and a total acquisition time of 21 min 20 s. To assure reproducible measurements, the MR slice was positioned by means of MR-visible markers, which were attached to the PG container directly after irradiation using the room lasers.

For the measurement within the electromagnet (section 2.2.2), the irradiated gel container was scanned $48$ h after the irradiation using the same imaging parameters. In both types of experiment, the isocenter was reconstructed using the MR-visible markers using a sequence with high spatial resolution ($0.5 \times 0.5 \times 0.5$ mm$^3$ with $TR = 6.5$ ms, $TE = 3.3$ ms, number of averages $= 2$ and a flip angle of $50^\circ$).

The acquired data was transferred to a personal computer and processed by an in-house developed Matlab (The Mathworks Inc., Natick, USA)-based PG evaluation tool to generate $T_2$-maps. A detailed description of the evaluation process has been described previously (Mann et al 2017).
Afterwards, both film and gel images were evaluated with the commercial software Mephisto (Version mcc 1.8, PTW, Freiburg, Germany). This software tracks the individual beams in the image by a regression to the maximum positions of the lateral profiles along the individual beams. The smallest circle touching or intersecting all beam axes, the so-called isocircle (IC) is automatically determined. In conventional linacs, the radius of this circle ($IC_r$) is a measure of the beam alignment for different beam angles. A second important parameter is the distance ($IC_d$) of the IC center to the isocenter as defined by the laser system, indicating the alignment of the machine rotation center to the room isocenter. To determine the mean and standard deviation of the two parameters, each parameter was determined by six repeated evaluations in Mephisto reflecting the reproducibility of the film evaluation.

In addition, the profile of each individual beam was determined as the average over nine profiles located at a radial distance of 21 mm–23 mm from the isocenter with a spacing of 0.25 mm (figure 2(a)). The maximum position of the profile was determined as the average of the maximum positions of the individual profiles.

### 3. Results

#### 3.1. Feasibility of polymer gel for star shot measurements

The evaluation of film and PG revealed comparable results for both $IC_r$ and $IC_d$ measurements (table 1). Furthermore, no significant changes over time were found for both parameters.

#### 3.2. Star shot measurements with and without magnetic field

Figure 2 displays the film and PG scans performed in the experimental electromagnet for 0 T and 1 T, respectively. The corresponding results are given in table 2. While $IC_r$ is well comparable for film and PG without magnetic field, $IC_d$ shows a difference of 0.3 mm. At 1 T, the $IC_r$ is increased markedly for film as well as for PG, while $IC_d$ still exhibited small values for both measurement methods.
Figure 3 displays the averaged relative lateral profiles as well as the maximum position for the five beam angles with and without magnetic field. The maximum positions determined by film and PG agree within the indicated uncertainty.

Table 1. Comparison of isocircle radii (IC\textsubscript{r}) and isocircle distance to the isocenter (IC\textsubscript{d}) for EDR3-film- and gel measurements (mean ± 1 SD). Uncertainty was determined by repeated evaluation with the Mephisto software.

|          | Film [mm] | PG (1 h) [mm] | PG (24 h) [mm] | PG (48 h) [mm] | PG (216 h) [mm] |
|----------|-----------|---------------|----------------|---------------|-----------------|
| IC\textsubscript{r} | 0.26 ± 0.02 | 0.27 ± 0.02 | 0.27 ± 0.03 | 0.26 ± 0.04 | 0.26 ± 0.04 |
| IC\textsubscript{d} | 0.70 ± 0.02 | 0.44 ± 0.03 | 0.40 ± 0.05 | 0.54 ± 0.05 | 0.38 ± 0.05 |

Table 2. Comparison of isocircle radii (IC\textsubscript{r}) and isocircle distance (IC\textsubscript{d}) to the isocenter for EBT3-film and PG measurements (mean ± 1 SD) with and without magnetic field. Uncertainty was determined by repeated evaluation with the Mephisto software.

| Magnetic field strength | Film [mm] | PG [mm] |
|-------------------------|-----------|---------|
| 0 T                     | IC\textsubscript{r} | 0.39 ± 0.01 | 0.44 ± 0.02 |
|                         | IC\textsubscript{d} | 0.82 ± 0.02 | 0.52 ± 0.03 |
| 1 T                     | IC\textsubscript{r} | 1.37 ± 0.01 | 0.97 ± 0.02 |
|                         | IC\textsubscript{d} | 0.12 ± 0.02 | 0.35 ± 0.07 |

Figure 2. Evaluated films ((a) and (b)) and PG-based T2-Maps ((c) and (d)) for magnetic field strengths of 0 T ((a) and (c)) and 1 T ((b) and (d)) with reconstructed beam axes (yellow), room lasers (red) and isocircles (blue). The blue boxes in (a) are located at radial distances between 21 mm and 23 mm from the isocenter and indicate the area over which beam profiles in figure 3 were averaged. As indicated in (a), the magnetic field is oriented towards the reader. The tics on the axes indicate 5 mm increments.
4. Discussion

In this work, it has been shown that the PAGAT polymer gel is a versatile tool for measuring the radiation isocenter accuracy by means of a star shot in the same way as it is standard for films. Both methods exhibit comparable results in terms of geometric parameters and although the absolute T2-values of the PG without magnetic field decrease from 460 ms (after 1 h) to 420 ms (after 2 d) in the intersection area of the nine beams, the resulting geometric parameters (ICr and ICd) only have a negligible dependence on the time point of the evaluation. Furthermore, the tolerance level for a star shot measurement of 0.5 mm (ICr), as recommended by the Task Group 142 report (Klein et al 2009), was always met. This means that the chemical effects of polymerization within 48 h post-irradiation do not play a major role, if only geometric parameters such as ICr and ICd are to be determined. This is a very important finding as it allows the evaluation of PG without any delay directly after irradiation. This is especially interesting for QA procedures for clinical MRgRT-devices.

Isocenter measurements using an electromagnet (section 2.2.2) without magnetic field revealed a slightly larger IC-radius for film and gel as compared to the standard star shot procedure (section 2.2.1), but still do not exceed the accepted limit of 0.5 mm. This increase can be explained by the rather complex experimental realization of the star shot in the presence of the magnet: due to the limitations in the accessible gantry angles, film and gel phantoms had to be rotated by 180° after irradiation of the first three beams to imitate a full gantry rotation. As this rotation is performed exactly around the axis of the magnet by construction of the film and PG holder, it may increase the isocircle radius due to a misalignment between the center of the magnet and the room isocenter.

To get an idea of how this positioning uncertainty of the magnet affects the isocircle radius, we performed a simple geometrical simulation, in which we used the open-source software Inkscape together with the lateral beam profiles in absence of the magnetic field to synthetically generate the gray-scale distribution of the five beams. Then beam set 2 (144° and 216°) was shifted against beam set 1 (0°, 72°, 288°) by the assumed positioning uncertainty and the evaluation was repeated for this new beam arrangement (figure 4). Since this procedure does not account for the effects of a magnetic field, it gives only a rough estimation of the expected increase of the isocircle radius. While a standard star shot with perfectly aligned beam axes performed outside the experimental magnet would exhibit an isocircle radius of 0 mm in this simulation, a shift of 0.5 mm between the center of the magnet and the room isocenter would increase the IC-radius to 0.46 mm.

In the presence of a magnetic field, the profiles are always deformed towards the same direction relative to the beam orientation due to the Lorentz force acting on the secondary electrons and the reconstructed maximum lines of the beams are displaced accordingly. As a result, the IC-radius is further increased. With this in mind, it has to be noted that the IC-radius is solely a measure of mechanical alignment in conventional linacs while there are two components in MRgRT-devices: (i) the unknown mechanical alignment uncertainty and (ii) the deformation of the beam profiles. While the first is the relevant parameter, the latter does not contribute to the overall uncertainty in a clinical setting as the deformation of the beam profile is considered in the beam model used for treatment planning and is compensated by the inverse dose optimization. Thus the interpretation of an increased IC-radius is complicated and its relevance has to be reassessed.
To circumvent this problem, van Zijp et al (2016) attached copper rings to the film to reduce the range of the secondary electrons and as a result, the isocircle radius at a 1.5 T-MR-Linac device was reduced from $2.35 \pm 0.35$ mm to $0.22 \pm 0.03$ mm. To apply this approach in combination with PG, the interaction of a copper ring with the polymer gel has to be investigated. Another way to compensate for the deformation of the lateral profiles could be the use of opposing fields for the star shot measurements, which would lead to symmetric profiles. Finally, comparison with Monte Carlo simulations could be done to separate the effect of the magnetic field from that of mechanical uncertainties.

With respect to the determination of the beam axis via the maximum positions of the lateral beam profiles, we would like to point out that although the profiles are not given in terms of absorbed dose, both films and PG result in well comparable maximum positions (figure 3). Remaining differences may be attributed to the necessary rotation of the detectors in our experimental setting. This additionally supports the finding that both methods yield comparable isocenter radii with and without magnetic fields.

The second parameter is the distance between the isocircle center and the room isocenter, $IC_d$. For this parameter, the largest deviation was found for the film measurement without magnetic field ($0.82 \pm 0.02$ mm), while all other measurements showed acceptable deviations of 0.5 mm or less. The variation of $IC_d$ is most likely caused by difficulties in aligning the magnet center accurately to the room isocenter and introduced inaccuracies when marking the laser lines on the film. It is expected that the parameter $IC_d$ is largely independent of the presence of the magnetic field as the beam directions are arranged symmetrically and as the deformation of the lateral dose distribution is always oriented towards the same side of the beam. In addition, as the results of film and PG measurements refer to independent measurements, a perfect agreement between both is also not expected.

Besides the positioning uncertainties of the magnet, one further source of error has to be mentioned: as the diameter of the pole shoes is only 7.5 cm, the magnetic field is rather inhomogeneous and the field strength drops to 50% at a distance of 5 cm from the center. The shift of the maximum of the beam profiles is therefore not constant along the beam axis, which may lead to somewhat different quantitative values of $IC_d$ as in case of a measurement in a clinical MR-Linac device.

Although star shot measurements with films and PG yield comparable results, a disadvantage of PG measurements is the high logistic effort due to the production, oxygen sensitivity and the MRI-based evaluation of the PG. On the other hand, however, our findings may allow the design of phantoms to check not only the radiation but also the imaging isocenter as the polymer gel is visible in MRI. Employing this finding in our study; that the PG can be evaluated directly after irradiation, future studies may investigate the use of PG to check the accuracy and coincidence of imaging and radiation isocenter of MRgRT-devices in a single measurement shortly after irradiation.

5. Conclusion

This study demonstrates that evaluation of the polymer gel directly after irradiation is feasible, if only geometrical parameters are of interest. This allows using polymer gels for star shot measurements to evaluate the radiation isocenter accuracy with comparable accuracy as with radiochromic films.
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