Polymer gel-based measurements of the isocenter accuracy in an MR-LINAC

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Abstract. As magnetic resonance-guided radiotherapy (MRgRT) is becoming increasingly important in clinical applications, the development of new quality assurance (QA) methods is needed. One important aspect is the alignment of the radiation and imaging isocenter. MR-visible polymer gels offer a way to perform such measurements online and additionally may allow for 3-dimensional (3D) evaluation. We present a star shot measurement irradiated and scanned with a 0.35 T MR-LINAC device evaluating the polyacrylamide gelatin (PAGAT) gel dosimeter immediately and 48 h after irradiation. The gel was additionally scanned at a 3 T MR device 5 h and 52 h after irradiation. The evaluation revealed an isocircle radius of 0.5 mm for both imaging devices and all image resolutions and time points after irradiation. The distance between radiation and imaging isocenter varied between 0.25 mm and 1.30 mm depending on the applied image resolution. This demonstrates that evaluation of a star shot measurement in a 0.35 T MR-LINAC is feasible, even immediately after irradiation.

1. Introduction
Integrating magnetic resonance imaging (MRI) into radiation devices, such as linear accelerators (LINACs) or 60Co-based systems [1-4], allows for image-guided radiation therapy (IGRT) improving the accuracy of dose delivery by acquisition of real-time images with excellent soft tissue contrast and without additional exposure of the patient. However, due to the static magnetic (B) field and the Lorentz force acting on the secondary electrons, the electrons will be deflected resulting in an altered dose distribution as compared to the case without magnetic field [5]. Therefore, the magnetic field changes not only the response of ionization chambers [6,7] but generates also asymmetric beam profiles [8], which may complicate geometrical quality assurance (QA) tests [9]: Most prominently, the isocircle radius, which is the smallest circle containing the central axis of all intersecting beams of a star shot measurement [10] - a well-established method for isocenter QA on conventional LINACs - will increase with increasing magnetic field strength. As a consequence, an increased isocircle radius cannot be attributed solely to mechanical machine misalignments. Therefore the interpretation of such tests also has to be reconsidered. To compensate for the effect of the magnetic field the use of high density material has been suggested [9].
Star shot measurements at conventional LINACs are usually performed with films. Using polymer gel (PG) instead, could offer a possibility to check the alignment between the irradiation and imaging isocenter [11] of MR-LINAC devices in 3D. Polymer gels [12] have revealed the same radiation isocenter accuracy as radiochromic films and can be evaluated immediately after irradiation, if only geometrical parameters are of interest [13]. In this paper we present the first irradiation of a star shot in PG within a 0.35 T MR-LINAC as well as the image-evaluation in the same device immediately and 48 h after irradiation. Additionally the PG was scanned with a 3 T MR device 5 h and 52 h after irradiation.

2. Material & Methods

2.1. Polymer gel

As PG the PAGAT (PolyAcrylamide Gelatin gel fabricated at ATmospheric conditions) [14] polymer gel was used (Table 1). A spherical flask composed of borosilicate glass was used as gel container (outer diameter = 8.5 cm, volume = 250 ml, wall thickness = 1 mm). The spherical flask was placed in the center of a cylindrical phantom (outer diameter = 23 cm) filled with a 3.6 g/l NaCl- and 1.25 g/l CuSO4-solution.

Table 1. Composition of the used PAGAT polymer gel in weight percent and mmol.

| Ingredient                                      | amount |
|-------------------------------------------------|--------|
| Water                                           | 89%    |
| Gelatine                                        | 6%     |
| Acrylamid                                       | 2.5%   |
| N,N'-methylene-bis-acrylamide                   | 2.5%   |
| bis[tetrakis(hydroxymethyl)phosphonium] chloride | 5mM    |

2.2. Irradiation

The phantom was first aligned with a clinical 0.35 T MR-LINAC (MRIdian, ViewRAY, Oakwood Village, OH, USA) by means of dedicated fiducials on the gel-filled flask using the laser-system of the device. In a second step, MR-images were acquired and an image-based correction was performed to position the phantom exactly at the image isocenter of the device. The irradiation was performed with five beams (0°, 72°, 144°, 216° and 288°), a field size of 0.4 x 2.49 cm² and 3 Gy per beam at the isocenter.

2.3. Evaluation

Immediately after irradiation, the phantom was scanned on the MR-LINAC using two consecutive single slice double spin echo sequence with the following imaging parameters: TR = 2000 ms, TE1,1 = 200 ms, TE1,2 = 600 ms, TE2,1 = 400 ms, TE2,2 = 800 ms, slice thickness = 20 mm, resolution = 0.5 x 0.5 mm² and 4 averages with a total acquisition time of 1 h 15 min each. Imaging was repeated 48 h after irradiation when the polymerization of the PG was known to be completed. At this time point, another measurement with a better signal to noise ratio (SNR) was acquired using TR = 4000 ms, TE1 = 200 ms, TE2 = 600 ms, slice thickness = 20 mm, three averages and resolution = 1.0 x 1.0 mm².

In addition, a measurement on a 3 T Biograph mMR (Siemens Healthineers, Erlangen, Germany) was performed 5 h after irradiation using a single slice multi spin echo with 32 equidistant echoes with the following imaging parameters: TR= 4000 ms, TE = 30 – 960 ms, slice thickness = 20 mm and a resolution of 0.5 x 0.5 mm² with a total acquisition time of 29 min 10 s. This measurement was also repeated 52 h after irradiation and additionally with a better SNR using a resolution of 1.0 x 1.0 mm².

The acquired images were processed by an in-house developed Matlab (The Mathworks Inc., Natick, USA)-based PG evaluation tool [15] to generate T2-maps. The images prepared in this way were evaluated with the commercial software Mephisto (Version mce 1.8, PTW, Freiburg, Germany). Each
beam was selected manually in the software and the isocircle was determined; this procedure was repeated 6 times to determine the standard deviation (SD) of the Mephisto evaluation.

3. Results

Figure 1 displays the evaluated T2-Maps for the different imaging devices and resolutions. The corresponding isocircle radii (ICr) consistently revealed values of 0.5 mm independent of the applied imaging device and image resolution (Table 2). Reproducibility as indicated by the standard deviation (SD) was better by a factor of two for the 3T MR-device. The distance (ICd) of the radiation isocenter, defined by the center of the isocircle, to the imaging isocenter, defined by the fiducials on the phantom, revealed values of up to 0.65 mm for the high- and up to 1.30 mm for the low-resolution images (Table 2).

| Table 2. Isocircle radii (ICr) and distance (ICd) for the different imaging devices and resolutions (mean ± 1 SD). |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| resolution [mm²] | time point [h] | ICr [mm] | ICd [mm] | time point [h] | ICr [mm] | ICd [mm] |
| 0.35 T MR-LINAC | 0 | 0.51 ± 0.11 | 0.25 ± 0.11 | 5 | 0.51 ± 0.05 | 0.61 ± 0.09 |
| 0.5 x 0.5 | 48 | 0.48 ± 0.06 | 0.65 ± 0.17 | 52 | 0.49 ± 0.03 | 0.44 ± 0.08 |
| 1.0 x 1.0 | 49 | 0.55 ± 0.06 | 1.30 ± 0.09 | 52 | 0.48 ± 0.03 | 1.03 ± 0.10 |

4. Discussion

This is the first study demonstrating the feasibility of star shot measurements in an MR-LINAC using PG. Although the images acquired with the 0.35 T MR-device of the MR-LINAC had a higher noise content than those of the 3 T device, well-comparable isocircle radii with clinically acceptable accuracy were obtained.

Since the 0.35 T MR-LINAC images with high resolution (0.5 x 0.5 mm² pixel size) showed a low SNR (Figure 1 (a) and (c)), an additional image with a resolution of 1.0 x 1.0 mm² was obtained 48 h after irradiation to analyze the effect of an improved SNR (Figure 1 (e)). As a result, the same isocircle radius was obtained indicating that the lower SNR of the high resolution images are still good enough for a quantitative evaluation. In contrast, the SNR of the images of the 3 T MR-device is much better even for the higher resolution (Figure 1 b,d,f), which however, did not lead to differences in the isocircle radii. It is thus feasible to determine geometric parameters like the isocircle radius even in images with very low SNR.

Additionally, it should also be mentioned that the automatic beam-fitting-algorithm of Mephisto was yet significantly less error prone using the MR-LINAC images with 1.0 x 1.0 pixel size in contrast to the 0.5 x 0.5 mm² pixel size.

The values determined for the isocircle distance are within the recommended tolerance limits for conventional LINACS (< 1 mm distance between the laser and the irradiation isocenter [16]) for measurements with 0.5 x 0.5 mm pixel size, for both images with 1x1 mm voxel size the values slightly exceed this recommended value. This is most likely due to the pixel size of 1 mm, which leads to an increased uncertainty in the determination of the fiducial position in the image. Since these fiducials represent the imaging isocenter, ICd may be increased.

Furthermore, it should be noted that the T2-map of the images recorded on the MR LINAC was determined using only 4 echoes ($R^2 = 0.90-0.94$), so that it can be assumed that the fit over all echoes is not as stable as in the case with 32 echoes (3 T mMR $R^2 > 0.98$). Unfortunately, there is no multi-spin-echo sequences available on the MR-LINAC device, yet, but it is expected to be implemented soon. Since we intend to use the presented measurement technique in the future to measure the alignment accuracy of irradiation and imaging isocenter in 3D with an uncertainty of below 1mm in axial direction, it is essential to reduce the slice thickness from 20 mm to at least 1 mm. For this, the signal
intensity is expected to drop significantly (SNR~slice thickness), which would further decrease the signal to noise ratio. This may be compensated by using more numbers of signal averages/acquisitions (NSA) (SNR~√NSA), which however, will increase the measurement time. Nevertheless, we expect that the combination of extended measurement time and the use of a multi-spin-echo sequence with 32 echoes will significantly enhance the signal of the images, so that even images with a significantly reduced slice thickness may provide sufficient information to perform irradiation and imaging isocenter measurements.

Figure 1. PG-based T2-Maps acquired with a 0.35 T MR-LINAC (a,c,e) and a 3 T MR device (b,d,f) at different time points after irradiation: immediately (a), 5 h (b), 48 h (c), 49 h (e) and 52 h (d,f) after irradiation. The magnetic field is orientated towards the reader. Resolution is 0.5 x 0.5 mm² (a-d) and 1.0 x 1.0 mm² (e,f). The isocircle is delineated in blue.
5. Conclusion
The evaluation of a star shot measurement in a 0.35 T MR-LINAC is feasible, even immediately after irradiation. Although the SNR was significantly worse than that of the 3 T device, well-comparable isocircle radii and isocenter distances were obtained for an image resolution of 0.5x0.5 mm². With this low magnetic field strength, however, significantly longer acquisition times are needed.

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