Polymer gel dosimetry in the presence of a strong magnetic field

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Abstract. The integration of magnetic resonance (MR) imagers with radiotherapy units provided a new opportunity to demonstrate the value of polymer gels as volumetric dosimeters. The purpose of this work was to investigate the use of methacrylic-acid based polymer gels for quality assurance of patient-specific treatment plans delivered with these novel treatment machines. The characterization of the gel was performed while the gel was subjected to a strong magnetic field and in the absence of the magnetic field. Additionally, an end-to-end phantom study was conducted using an MR image-guided radiotherapy (MR-IGRT) unit. This data will be used to support the implementation of volumetric dosimeters in MR-IGRT.

1. Background

Novel treatment modalities integrate magnetic resonance imaging (MRI) with a linear accelerator or with 60Co sources for volumetric image guidance during radiation therapy. Several different designs of radiotherapy units integrated with magnetic resonance imaging have been introduced recently [1-4].

Using MRI for image guidance has advantages over conventional computed tomography (CT) or cone-beam CT: The patient is not exposed to any additional imaging dose during the course of the treatment; MRI provides superior image contrast allowing for a more accurate delineation of the tumor and adjacent organs; and it enables more accurate adaptation of the patient's treatment plan through the use of MR image acquisition for assessment of inter- and intra-fraction changes.

Lorentz forces are exerted on secondary electrons produced during photon interactions in the presence of a magnetic field and lead to a three-dimensional shift in delivered dose distributions in phantoms and patients. The magnetic field limits the use of, or requires modifications of electronic detectors used for quality assurance (QA) of the machines and for QA of patient-specific treatment plans. Several vendors provide MR-compatible electronic dosimeters that measure dose distributions at best in quasi-3D. Hence, 3D detectors such radiochromic plastics, radiochromic gels, and polymer gels have been suggested for MR image-guided radiotherapy (MR-IGRT) treatment plan verification [5].

Polymer gels have been used to measure complex dose distributions with steep dose gradients using an MR scanner for readout. The spin-spin relaxation rates (R₂) of the irradiated polymer gel change due to radiation-induced polymerization and increase monotonically with an increase in dose. These changes in R₂ can be measured with MRI [6-8] making polymer gels favorable detectors for QA of MR-IGRT units.
This paper presents two sets of data: the characterization of a polymer gel in the presence of a strong magnetic field and an end-to-end phantom study performed with an MR-IGRT treatment unit. Characterizing a polymer gel shed light into potential effects of the magnetic field during irradiation and the end-to-end phantom study was used to advocate the implementation of polymer gel dosimeters in MR-IGRT.

Experiments initially performed with methacrylic-acid based polymer gels (MAGAT) on an orthovoltage unit (Philips RT-250) found a dose-rate dependence of up to 30% at low dose rates [9]. Both De Deene et al. [10, 11] and Bayreder et al. [12] performed studies that concluded a dose-rate dependence when methacrylic acid was the monomer source in the polymer gel dosimeters. Hence, before commencing studies with a different methacrylic-acid based polymer gel (BANG3-Pro) information was requested from the manufacturer (MGS Research, Madison, CT) who stated that this particular formulation was neither dose-rate dependent nor energy dependent [15]. This statement was based on the investigations performed by Massillon-JL et al. [13] and Massillon et al. [14] whose findings supported a dose-rate independence and a fractionation independence of this gel formulation.

2. Methods
Methacrylic-acid based polymer gel (BANG3-Pro) dosimeters were provided by the manufacturer (MGS Research, Madison, CT) in customized glass vials of 5 cm diameter and 4 cm height. The design enabled the initial characterization of the polymer gels using an electromagnet (GMW Dipole Electromagnet 3472-70, GMW Associates, San Carlos, California) installed in a vault that housed a cobalt unit (Theratron 780C, AECL, Chalk River, Canada) and subsequently in a vault that housed a Versa HD linear accelerator (Elekta AB, Stockholm, Sweden). These measurements were performed prior to the installation of an MR-linac (Elekta in collaboration with Philips Medical Systems, Best, The Netherlands); a 7 MV linear accelerator integrated with a 1.5 T MR scanner.

The dose response, dose-rate dependence, and fractionation dependence of the polymer gel were investigated in the cobalt beam and in the 6 MV photon beam from the Versa HD linac in the absence of a magnetic field. Dose response measurements were repeated inside a strong magnetic field using the electromagnet inside the linac vault. Following the installation of the MR-linac, the dose-rate dependence and fractionation dependence of the gel were evaluated with the MR-linac.

To assure full scatter conditions all glass vials were irradiated one at a time inside a full water-equivalent phantom at 10 cm depth. Twenty-four hours after exposure the irradiated gels were scanned with a GE 3 T MR scanner (GE Discovery MR750, Waukesha, Wisconsin). $R_2$ values were determined from the MR images. For end-to-end testing of the MR-image guided treatment process, a large, spherical dosimeter filled with the same polymer gel was positioned and irradiated on the MR-linac.

2.1. Dose response
A dose response curve was acquired by placing five dosimeters inside a full phantom and irradiating them to 1, 3, 5, 7, and 9 Gy using a cobalt irradiator at a dose rate of approximately 64 cGy/min. The dose response measurements were repeated by delivering the same dose levels with Versa HD linac to five additional dosimeters while they were exposed to a 1.04 T magnetic field that was generated with an electromagnet. The electromagnet was positioned at a distance of 300 cm away from the radiation source while the gantry was rotated to 90 degrees to avoid any interference of the magnetic field with the linear accelerator.

Due to the differences in setup the dose response curves acquired with the cobalt irradiator (B = 0 T) and the Versa HD linac (B = 1.04 T) could not be directly compared. To confirm the response of the gel to 6 MV radiation two additional dosimeters were irradiated to 5 Gy and to 9 Gy after the magnetic field of the electromagnet was turned off.

$\Delta R_2$ values were obtained from MR images for all irradiated dosimeters one day after exposure and were plotted against the respective dose values. A linear fit was applied to the two dose response data sets when B = 0 T and the data set when B = 1.04 T. The slope of the linear fit obtained from two data
points with $B = 0$ T was compared to the slope of the linear fit obtained from five data points with $B = 1.04$ T.

2.2. Dose-rate dependence
A change in dose rate was achieved with the Versa HD by extending the distance between the dosimeter and the radiation source. Ten Gy were delivered to a dosimeter inside a full phantom at a source-to-surface distance (SSD) of 100 cm. A second dosimeter was exposed to the same dose after the setup was moved to an extended SSD of 290 cm. The dose rate at the extended SSD was 14% of the rate at the standard treatment distance. $\Delta R_\text{2}$ values were compared between the standard and extended SSDs.

Due to the fixed source-to-isocenter distance of the MR-linac the dose rate was changed at the console. Ten gray were delivered to a dosimeter at a dose rate of approximately 450 cGy/min (100%) and to a second dosimeter at a dose rate of approximately 63 cGy/min (14%). The lower dose rate was chosen for consistency with the irradiations with the Versa HD linac. The $\Delta R_\text{2}$ values from the irradiations with high and low dose rates were compared.

2.3. Fractionation dependence
A dose of 10 Gy was delivered to one gel dosimeter in a single fraction using the Elekta Versa HD. The same dose was delivered to another dosimeter in three fractions of 3.33 Gy each. The time between each fraction measured 9 minutes, to yield a total irradiation time of 21 minutes, for consistency with the low-dose rate irradiations. $\Delta R_\text{2}$ values were determined from MR scans a day after irradiation and compared between single fraction and multiple fractions.

The same dose delivery pattern was repeated using the MR-linac with an equal time between each fraction. Again, $\Delta R_\text{2}$ values from the single fraction dose delivery were compared to the multiple fraction dose delivery.

2.4. End-to-end phantom study
The workflow used in MR-IGRT was followed with the spherical gel dosimeter to perform a full end-to-end phantom study with the MR-linac. CT images of the dosimeter were used to create a reference treatment plan. The CT images were fused with MR images acquired with the MR-linac prior to irradiation to generate an adapted plan with the Monaco treatment planning system (research version 5.19.02). A dose of 7.5 Gy was delivered according to the AAPM TG-119 head and neck treatment plan [16]. The head and neck plan consisted of nine IMRT beams that were delivered in a step-and-shoot fashion. Dose constraints were set for structures drawn to represent a head and neck PTV, a spinal cord, and parotid glands. The dosimeter was MR imaged again for dose analysis 24 hours post-irradiation. A 3D gamma analysis was performed on dose maps using 3D Slicer with the SlicerRT extension [17]. IROC Houston has determined that a minimum of 85% of all analysed pixels must pass 7%/4 mm gamma criteria with a 10% dose threshold for a head and neck phantom to pass the QA test [18]. The results of the 3D gamma analysis were compared with the IROC passing criteria.

3. Results and Discussion

3.1. Dose response
$R_\text{2}$ values exhibited a linear increase with dose when dose response measurements were performed with the cobalt irradiator. A straight-line fit resulted in a slope of 0.0104 s\(^{-1}\)cGy\(^{-1}\) and an intercept of 6.830 s\(^{-1}\). The standard deviation was calculated for each dose level and displayed as error bars in Figure 1 (A).

When irradiated with 6 MV photons inside a 1.04 T magnetic field, the dose response curve of the polymer gels appeared linear up to a dose of 9 Gy as the black diamonds indicate in Figure 1 (B). A linear fit provided a slope of 0.0144 s\(^{-1}\)cGy\(^{-1}\) and an intercept of 9.612 s\(^{-1}\). The red squares in Figure 1 (B) show the $R_\text{2}$ values measured at 5 Gy and at 9 Gy. Connecting the two points with a straight line was supported by the linearity of measurements performed with the cobalt irradiator. A linear fit generated a slope of 0.0144 s\(^{-1}\)cGy\(^{-1}\) and an intercept of 9.514 s\(^{-1}\).
R$_2$ values obtained at 5 Gy and at 9 Gy differed by 0.4% and by 0.5%, respectively, when comparing measurements with and without a magnetic field. This difference was smaller than the 2% to 3% uncertainty of R$_2$ values. Both dose response curves exhibited the same slope therefore, no apparent difference between the two dose response curves could be determined as. Any influence of the magnetic field on the dose response was smaller than the uncertainty in the measurements.

![Figure 1](image.png)

**Figure 1.** Dose response curves using (A) a cobalt irradiator and (B) a Versa HD linear accelerator and an electromagnet. Error bars represent one standard deviation.

3.2. Dose-rate dependence and fractionation dependence

Table 1 shows that $\Delta$R$_2$ values measured at the reduced dose rate at extended distance were 26% higher than the values at 100 cm SSD. A corresponding 86% reduction in dose rate on the MR-linac resulted in a 24% increase in $\Delta$R$_2$ values compared to delivering the same dose at 100% dose rate. The difference of 2% in measurements with and without a magnetic field fell within the uncertainty of $\Delta$R$_2$ measurements of 2% to 3%. No apparent effect of the magnetic field on the dose-rate dependence was detected.

The $\Delta$R$_2$ value at 10 Gy determined from the linear fit of the dose response in Figure 1 (A) was lower than a $\Delta$R$_2$ of 10.80 s$^{-1}$ measured with the 6 MV photon beam at 100% dose rate. However, the reported dose-rate dependence suggests that the response measurements using the cobalt irradiator would yield higher $\Delta$R$_2$ values. This difference reflects the use of different batches of BANG3-Pro gel through the course of this study.

| B = 0 T | B = 1.5 T |
|--------|---------|
| dD/dt = 14% | dD/dt = 100% | dD/dt = 14% | dD/dt = 100% |
| $\Delta$R$_2$ [s$^{-1}$] | 13.63 | 10.80 | 12.30 | 9.93 |
| ratio $\Delta$R$_2$ | 1.26 | 1.24 |

Table 2 shows 8% higher $\Delta$R$_2$ values when the dose was delivered in multiple fractions compared to when the same dose was delivered in a single fraction. When irradiated in a magnetic field, 8% higher $\Delta$R$_2$ values were obtained when delivering the same dose in multiple fractions compared to a single fraction. No difference in ratios of $\Delta$R$_2$ values was determined when investigating fractionation
dependence of the polymer gel in the presence and absence of the magnetic field. These results lead to the conclusion that the fractionation dependence was independent of magnetic field.

| Table 2. Fractionation dependence measurements. |
|-----------------------------------------------|
| B = 0 T | B = 1.5 T |
|        | multiple fx | single fx | multiple fx | single fx |
| ΔR₂ [s⁻¹] | 11.72 | 10.80 | 10.72 | 9.93 |
| ratio ΔR₂ | 1.08 | 1.08 | 1.08 | 1.08 |

Studies have indicated that dose-rate dependence and fractionation dependence were correlated [19]. Hence, it was not surprising that both a high dose-rate dependence and a significant fractionation dependence were observed with this polymer gel.

3.3. End-to-end phantom study

Figure 2 (A) (left) shows the scale of the planned dose distribution that ranged from 0 Gy (shown in green) to 7.5 Gy (shown in red). The same scale was used for the gamma maps in Figure 2 (B) (right) ranging from 0 in green up to 1 in yellow and >1 in red. A black line was included on the gamma map to indicate the horseshoe-shaped PTV. The sparing of the spinal cord was visible from the horseshoe shape of the dose distribution seen on the axial views in Figure 2. The indentations in the dose distribution indicate the sparing of the parotid glands which was seen on coronal views (not shown). A gamma pass rate of 85.6 % was determined using the IROC head and neck 7 %/4 mm gamma criteria and a 10 % dose threshold.

![Figure 2](image)

Several reasons were considered for the less than expected gamma pass rates. The gamma maps for each slice indicated that the gamma analysis failed in regions of beam entrance and exit inside the dosimeter. This could be due to the high dose-rate dependence. Also, the MR signal was scaled to the prescription dose using T₂-weighted MR images instead of R₂ maps.

4. Conclusion

For the first time, an MR-IGRT treatment system was used to deliver and analyze a dose distribution in a clinically relevant volume with a polymer gel dosimeter. The polymer gel with its current chemical composition worked well for visualizing the complex 3D dose distributions delivered with the MR-linac.
However, the strong dose-rate dependence and the non-negligible fractionation dependence rendered the gel unsuitable for clinical dosimetry and for quality assurance of patient-specific treatment plans. The strong dose-rate dependence is of concern as IMRT and VMAT dose deliveries exhibit steep dose gradients and varying dose rates due to beam modulation and to differences in the depths of tissue penetrated during delivery. This dependence can lead to an overestimation of the signal in regions of lower dose rates. Furthermore, due to the fractionation dependence a further overestimation of the measured dose can occur when the treatment is heavily modulated or has to be interrupted. Therefore, minimizing these dependences is essential to perform accurate multi-beam or modulated treatment plan validation.

These results warrant the investigation of non-methacrylic-acid based polymer gels so that they can be used as clinical, 3D dosimeters for MR-IGRT.

5. References
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