Real time 4D Radiation Gel Dosimetry on the Australian MRI-Linac

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Abstract. 4D radiation dosimetry using a highly radiation-sensitive polymer gel dosimeter with real-time quantitative MRI readout is presented as a technique to acquire the accumulated radiation dose distribution during image guided radiotherapy (IGRT) on an MRI-Linac. Optimized T2 weighted TSE scans are converted into quantitative $\Delta R_2$ maps and subsequently to radiation dose maps. The potential of real-time 4D radiation dosimetry in a theragnostic MRI-Linac is demonstrated in test tubes, for a square beam in a cylindrical gel phantom, for a simple step-and-shoot irradiation in a head phantom and a dynamic arc treatment on a cylindrical gel phantom using a rotating couch. The optimal sequence parameters for maximal dose resolution in the dynamic MRI acquisition will be presented and the trade off between MRI scanning speed and dose resolution will be discussed. A further improvement in temporal resolution using a keyhole imaging approach is the focus of future research.

1. Introduction

For decades, gel dosimeters have been proposed and applied in radiotherapy (RT) to display the radiation dose distribution in three dimensions [1, 2]. We here present the first results of online MRI of a radiation sensitive polymer gel dosimeter, imaged on the Australian MRI-Linac during radiation. While gel dosimetry has been applied on an MRI-Linac previously [3-5], this is the first study that demonstrates the feasibility of real-time 4D gel dosimetry. The possibility to image the gel dosimeter in pseudo-real time also sheds some light on short term chemical processes inside the polymer gel dosimeter. These early results demonstrate the potential of real time radiation dosimetry of MRI guided radiotherapy. An increase in readout speed is feasible with keyhole MRI.

In order to acquire real time dose maps, the dosimeter needs to have a high MRI dose sensitivity, exhibit a fast radiation response and be tissue equivalent. The post-irradiation response should be as low as possible. Moreover, like other 3D gel dosimeters, favorable characteristics are a good temporal stability, a high spatial integrity, a low temperature sensitivity and low dose rate dependence. We found that a Methacrylic Acid based polymer gel dosimeter [6] has a high dose-$R_2$ sensitivity and satisfies most of the aforementioned criteria.

2. Methods and Materials

2.1. Manufacturing of the Polymer Gel Dosimeter

Polymer gel dosimeters (PGDs) based on 6% (w/w) methacrylic acid and 8% (w/w) gelatin, referred to as MAGAT, were fabricated according to a recipe discussed elsewhere [6]. Four different sets of
phantoms were fabricated: 14 test tubes that served as calibration vials, two 1L cylindrical flasks (diam. 10 cm) and a 3L head phantom.

2.2. Rotating Couch for the MRI-Linac
In the Australian MRI-Linac, the Linac (Linatron-MP, Varian Medical Systems) is static with respect to the patient table and MRI scanner. To enable a rotational dynamic treatment, an automated rotating phantom holder was constructed in house. The construction of the rotating phantom system will be discussed elsewhere [7].

2.3. MRI Scanning and Irradiation
MRI scanning and irradiation of the PGDs was performed on the 1T MRI-Linac. The phantoms were also scanned 26 hours post-radiation on a clinical 3T MRI (Siemens Verio).

The calibration vials were irradiated in a standard water phantom at reference depth (10 cm). The dose rate at reference depth was 1 Gy/min. During radiation, the calibration gel dosimeters were scanned repeatedly inside the receive head coil with a T2\textsubscript{w} Turbo-Spin Echo (TSE) sequence (TE: 271 ms; TR: 2 s; NEX: 2; Turbo Factor (TF): 22; Bandwidth per pixel (BW): 275 Hz/pixel; FOV: 200 mm; MS: 256×256; d: 5 mm). A single scan took 48 s. Immediately after radiation exposure, the gels were scanned with a Multi-Spin-Echo (MSE) sequence with 32 echoes spaced at 15 ms from which a calibration curve was obtained that was used to convert all dynamic scans to dose maps (Figure 2).

A 1L cylindrical gel phantom (diam. 120 cm) was irradiated with a 3 cm × 3 cm 6 MV photon beam in the longitudinal direction. The gel phantom was scanned dynamically with a TSE sequence with similar sequence parameters as above but with a FOV of 171 mm.

Another 1L cylindrical gel phantom (diam. 110 cm) was inserted in the rotating coach and irradiated with a lateral 2.6 cm × 2.6 cm beam that was placed 3 cm off axis with respect to the cylindrical phantom. The phantom was rotated in incremental steps of 9 degrees every 18 seconds while the beam was kept on during the entire radiation. The dose rate at isocenter for the radiation beam was set at 100 cGy/min. The total radiation treatment was split in 3 parts (each corresponding with a rotation over 120 degrees), between which the Linac was allowed to cool down for a few minutes.

The head phantom was exposed with 3 coplanar beams at angular increments of 120 degrees. For each of the 3 directions, the phantom was automatically rotated by use of the rotating couch. Dynamic TSE scans were taken with imaging parameters: FOV/MS/d/TR/TE/TB/W = 220 mm/192/10 mm/1 s/160 ms/130 Hz. The time between two consecutive scans was 11 seconds with 10 seconds effective scanning and 1 second delay time.

The TSE images were converted to dose maps by a procedure as outlined in Figure 2. The calibration phantoms were also scanned with a multi-spin echo (MSE) sequence with 32 echoes and echo time spacing of 15 ms. R2 maps were constructed from the 32 contrast weighted base images by use of an exponential fit on a pixel-by-pixel basis. The R2 values for each of the calibration vials were extracted from circular regions of interest taken inside the test tubes and an R2-dose plot was obtained. The change in R2 as a result of radiation can be extracted from the ratio of the signal intensity in a dynamic TSE scan recorded before radiation (S(0)) and the signal intensity (S(\textit{t})) in a dynamic TSE scan recorded during radiation at time \textit{t} by use of equation 1.
A bi-exponential fit on the $R_2$-dose calibration plot was used to convert the $\Delta R_2$ values to dose values.

$$\Delta R_2 = \frac{1}{TE} \ln \left( \frac{S(0)}{S(t)} \right)$$  \hspace{1cm} (1)

3. Results and Discussion

The dose-$R_2$ response of the MAGAT PGD follows a bi-exponential function on both the 1T MRI-Linac and on the 3T MRI scanner. The sensitivity of the MAGAT PGD in the linear region of the dose-$R_2$ response curve was found to be 3.95 s$^{-1}$ Gy$^{-1}$ on the MRI-Linac immediately after radiation and was found to be 4.5 s$^{-1}$ Gy$^{-1}$ 26 hours after irradiation on the 3T MRI scanner. The difference in dose sensitivity is attributed to post-irradiation polymerization. Real-time recorded dose maps show a nearly linear increase over time in recorded dose during radiation (Figure 3), and an exponential saturating response with a time constant of 80 minutes indicating post-irradiation polymerization. A model is derived to describe and fit the radiation response in the gel as a function of time during radiation (figure 3c). Assuming a first order kinetic response on radiation, it can be shown [8] that the registered dose is given by

$$D_r(t) = \dot{D} t + \dot{D}_r (e^{-t/\tau_r} - 1) \quad \text{for } 0 \leq t \leq t_{ON}$$  \hspace{1cm} (2)

$$D_r(t) = \dot{D}_r t_{ON} + \dot{D}_r e^{-t_{ON}/\tau_r} (e^{t_{ON}/\tau_r} - 1) \quad \text{for } t \geq t_{ON}$$  \hspace{1cm} (3)
where \( \dot{D} \) is the dose rate, \( \tau_r \) is the time constant of the post-irradiation response and \( t_{ON} \) is the time that the beam is on.

Figure 3. Sagittal measured dose maps obtained from T\textsubscript{2w} TSE scans acquired at the 3T MRI-Linac. Calibration vials (a) were irradiated at reference depth in a water phantom. A cylindrical flask was irradiated with a small 2 cm × 2 cm beam (b). The change in registered dose over time demonstrates a post-irradiation response with a time constant of 83 s (c). The red shaded area is the response when the beam was on, while the green shaded area is when the beam was switched off.

Dose maps recorded during a dynamic arc treatment with off centre beam are shown in figure 4.

Figure 4. MRI measured dose maps (central slice) during a rotational treatment on a cylindrical phantom. The separation between two adjacent images is 7 recorded frames, corresponding with an angular increment of 54 degrees.

A movie of the dose formation can be found here:
The angular variation in dose in the final dose maps is attributed to an instability in dose rate during radiation which was confirmed from the logs on the Linac. Dynamic dose maps of the head phantom at different time points during radiation are shown in figure 5. Every row corresponds to a different angle of radiation. The time between different rotation angles was approximately 14 minutes during which the beam was switched off. A movie containing all frames recorded at 11 second intervals is provided as supplementary material (https://www.dropbox.com/s/xwfxb98kgfltv6d/Head.avi?dl=0). The post-irradiation polymerization is visible between frames when the beam direction was changed (i.e. between the last image in a row and the first image of the next row in figure 5).

![Dose Maps](https://www.dropbox.com/s/xe30c3ty63aezwc/Cylinder.avi?dl=0)

**Figure 5.** MRI measured dose maps recorded during radiation of a head phantom with three beams. Between each row, the phantom was rotated by 120 degrees to deliver the next beam. The time stamps above each dose map indicate the time since the start of radiation. No radiation was delivered between each rotation (i.e. between each row).

### 4. Conclusions

It is demonstrated for the first time that 4D radiation dosimetry with polymer gel dosimeters is feasible. The polymer gel dosimeter has a good stability but still shows some post-irradiation polymerization after radiation exposure. The time constant of this post-irradiation polymerization is in the order of 80 seconds. While these preliminary results are obtained on an experimental 1T MRI-Linac with relatively low dose rate, it can be expected that higher SNR is achievable at a 1.5 T MRI-Linac. A more extensive discussion on the important properties, optimization and limitations of gel dosimetry for real time dosimetry on an MRI-Linac can be found elsewhere [8]. For higher dose rates and for the compensation of organ motion, a higher frame rate without sacrificing SNR is achievable by using a keyhole approach. Such an imaging sequence is currently under development.

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