Volume-dependent internal temperature increase within polymer gel dosimeters during irradiation

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Abstract. The increase in temperature within polymer gel dosimeters due to exothermal polymerization reactions was measured during irradiation inside two normoxic polymer gels (MAGAT and PAGAT) with different volumes (from 18 ml to 257 ml) at a dose rate of 3.0 and 0.5 Gy.min⁻¹. The same samples were evaluated by MRI the day after irradiation. The temperature rise is clearly a function of the irradiated gel volume and for the MAGAT gel dosimeter it is almost twice that of the PAGAT dosimeter. Herein, we report on the experimental set-up, preliminary temperature measurements and the corresponding MRI results.

1. Introduction

In performing dose measurements with polymer gels a chain of procedures from fabrication of the gel, filling the appropriate phantoms, transporting, positioning, irradiating, calibration and finally scanning is to be followed, each of which requires careful attention to the details that may impact on the gel response. Accordingly numerous authors have reported the effect and severity of different factors that may alter the final dose determination. Among these is the temperature, which is known to affect most dosimetric measurements. However, polymer gel dosimeters are unique in that not only the ambient temperature affects their results [1], but the exothermal polymerization reaction [2] causes the temperature of the gel to increase during irradiation. Although this temperature rise has been recognized and its possible effects were previously hypothesized [2,3], no experimental attempt has been made to fully evaluate whether or not the gel response as determined by MRI is altered by these internal temperature changes.

The magnitude of the temperature rise is a function of the number of moles of reactions occurring per unit time [2], therefore it depends on the nature and concentration of the monomers, on the irradiated volume of gel, on the dose rate as well as on the rate of heat loss associated with the material and thickness of the container.

It was suggested that if the temperature increase in gel dosimeters affects the dynamics of polymerization reactions or the final polymer morphology, then the test tube calibration method might not always provide accurate results since the small volume of gel in the test tubes would not experience the same temperature changes as larger volumes of a phantom of interest [2,3].
Figure 1. Less polymerization in test tubes results in dose overestimation and vice versa.

In fact several groups have observed dose deviations between calibration vials and larger phantoms originating from the same batch of gel [4]. Different potential causes were hypothesized for this phenomenon [3,4] and some discrepancies are difficult to reproduce [5,6].

Assuming that less polymer is formed in small calibration test tubes, the dose in the phantom of interest would be overestimated by that calibration and vice versa. This is depicted in Figure 1 where three presumed calibration curves are drawn, showing the correlation between the spin-spin relaxation rates ($R_2$) and absorbed dose.

The objective of this work is to experimentally investigate the extent of temperature increase in different polymer gel dosimeters for different doses, dose rates and volumes of gel as well as its possible impact on the gel dose-response. Our preliminary temperature measurements are presented here.

2. Materials and Methods

Eight MRI-compatible optical temperature sensors (NeOptix Inc, Quebec, Canada, accuracy ±1°C, resolution 0.1°C) were used to measure the temperature inside the phantoms. The standard probes were protected by a thin Teflon jacket. We found this jacket released oxygen in the polymer gel dosimeter such that areas where $R_2$ remained constant after irradiation were detected around every probe (Fig. 2a). At our request, the company developed a new polyimide sheathing that does not cause oxygen contamination of the dosimeter gel (Fig. 2b). The outer diameter of the polyimide-coated optical fibers was 0.7 mm. Four cylindrical gel containers were constructed from Delrin® with an identical wall thickness of 2.5 cm and height of 15 cm. The outer diameters ranged in an increasing order from 6.0, to 7.5, 8.5 and 10 cm; the corresponding volumes were 18, 57, 150 and 275 ml respectively. The thickness of the base of the containers was 4 mm. Four holes were drilled at the same location in the walls of each container, allowing temperature probes to be inserted into the gel at different positions (Fig. 2c). Two normoxic gel formulations were studied, namely the polyacrylamide based gel (PAGAT) and the methacrylic acid based gel (MAGAT) dosimeters. Tetrakis (hydroxymethyl) phosphonium chloride (THPC) was used in both dosimeter gel formulations. The optimized formulations and fabrication procedures were reported [6,7]. The probes were inserted into desired positions, the phantoms were filled with the gel and placed in a water tank in a conventional refrigerator for about 5 hours for the gel to set. The water tank was then transferred to the radiotherapy department to acclimatize with the room temperature for 24 hours. In some cases pre-irradiation MR images were obtained to verify the homogeneity of the gel before irradiation in the four phantoms. The phantoms were previously CT-scanned and the CT images were transferred into a Pinnacle™ Treatment Planning System with which the dose delivery has been optimized for a 10 x 10 cm² field with 6 MV photons such that identical depths in all four phantoms received identical doses. A dose of 12 Gy to $D_{max}$ in water was delivered with high (300 MU/min) and low (50 MU/min) dose rates for the first series of experiments reported here [Siemens Oncor™ Linear Accelerator (Siemens Medical Solutions AG, Germany)]. Each phantom was transferred from the first water tank into a second water tank with an identical stable water temperature, it was irradiated then transferred back to
Figure 2. \(T_2\)-weighted MR images of four phantoms containing optical temperature sensors. (a) Sensors with a Teflon jacket through which oxygen could diffuse resulted in the inhibition of the polymerization of the gel around the probes in the phantoms (green arrows). (b) The Teflon jacket was replaced by polyimide sheathing which has a much lower permeability to oxygen. The MRI slices shown correspond to position 3 in the experimental set-up depicted in (c).

Figure 3 shows the temperature recorded by the probe in position 3 as a function of time (as shown in Fig. 2c) for high (a-d) and low (e-h) dose rates and the two gel dosimeters. The dose at position 3 of all four phantoms was 10 Gy in these experiments. The temperature increase in position 1 was always lower than in position 2 and 3 even if the dose at this point was higher. This is tentatively rationalized by the geometry of the phantomes where the base is thinner than the side walls. The maximum temperature rise for MAGAT as can be seen on (h) is up to two times larger than for the PAGAT dosimeter. The temperature rise for the PAGAT dosimeter was slightly higher at the higher dose rate for all volumes of gel. For the MAGAT dosimeter, on the other hand, a lower temperature increase was observed in the smallest container with the low dose rate (compare a and e) and a higher temperature increase was observed in the largest phantom with low dose rate (d and h).

For high dose rate irradiation of PAGAT gel dosimeter our preliminary MRI measurements reveal no significant difference between profiles of \(R_2\) along the central axis of the three larger phantoms, but the smallest phantom (18 ml) shows higher \(R_2\) values of the order of 6% along the depth. This suggests that termination reactions are favored in the larger containers by the heat that is produced in the gel dosimeter through polymerization.

3. Results and Discussion

The temperature measurement continued for a few hours then the phantoms were taken to the MRI room and scanned 24 hours later with a 1.5 T clinical scanner (Siemens Sonata, Erlangen, Germany) according to a previously optimized multi-spin echo protocol. The probes were not removed from the gel to avoid distortion to the surrounding gel.
Figure 3. Temperature differentials in position 3 as shown in figure (2c) for different volumes of MAGAT (red circles) and PAGAT (blue crosses) gels irradiated with 6 MV photons at two dose rates. The dose at this position was 10 Gy. Graphs a-d, refer to a dose rate of 300 MU/min and graphs e-h depict temperature changes for a dose rate of 50 MU/min. Start and end of irradiations are also shown by vertical lines. The phantoms were in water before, during and after irradiation.

The results are qualitatively similar to those we have previously reported [8]. We have yet not observed reproducible discrepancies between the four phantoms for other studies with MAGAT and low dose rate irradiations. As the rate of heat release may be considered proportional to the rate of
polymerization, these studies may provide additional information on the nature of polymerization reactions in polymer gel dosimeters.

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