



Performance evaluation of MRI-based PAGAT polymer gel dosimeter in an inhomogeneous phantom using EGSnrc code on a Co-60 machine

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ABSTRACT

Relative isodose curves were obtained using PAGAT gel dosimeter on homogeneous and inhomogeneous phantoms. Distance-to-agreement (DTA) was calculated between simulated and measured values for both the homogeneous and inhomogeneous phantoms. All DTAs except one passed the acceptance criterion (± 5 dose variation for selected isodose levels). Results of this study also showed the ability of the Monte Carlo modeling to provide accurate dosimetry, and revealed that the dose response of PAGAT polymer gel is dependent on the method of fabrication.

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1. Introduction

Polymer gel dosimetry is a technique that has the ability to map absorbed radiation dose distributions in three dimensions (3D) with a high spatial resolution. Polymer gel dosimeters offer a number of advantages over the traditional dosimeters such as ionization chambers, thermoluminescent dosimeters (TLD) and radiographic films. The advantages include independence of radiation direction, radiological soft tissue equivalence, integration of dose for a number of sequential treatment fields, and perhaps most significantly, evaluation of a complete volume at once. Several reviews on the polymer gel dosimetry systems have been presented previously (DOSGEL, 1999, 2001, 2004, 2006).

Important functionality of radiation dosimeters is its ability to measure absorbed dose with an acceptable precision and accuracy. For three-dimensional dosimeters such as the gel dosimeters the accuracy and stability is not only related to the measured dose value but also to the spatial integrity of the absorbed dose distribution. Therefore, in the case of the polymer gel dosimeters, it is crucial that a set of dosimetric properties is verified with respect to both dose and spatial accuracy. In the past, PAGAT gel compositions with various concentration of its

components have been proposed as potential three-dimensional dosimeter and many of its radiation properties have been tested thoroughly (Venning et al., 2004, 2005, 2006; De Deene et al., 2006).

In this study, the PAGAT polymer gel formulation was prepared on the bench with the addition of a 5 mM concentration of the tetrakis (hydroxymethyl) phosphonium chloride (THPC) anti-oxidant but with two different fabrication method as proposed by De Deene et al. (2006) and Venning et al. (2005).

Several studies have been performed for investigating the effects of inhomogeneities on dose distribution using MC simulation along with conventional dosimeters (Lewis et al., 2000; Moskvina et al., 2004; Al-Dweri et al., 2005; Cheung and Yu, 2005), but in the case of polymer gel dosimetry is rare (Haraldsson et al., 2006). The degree of accuracy that can be attained by MC simulation is determined mainly by the following factors:

- The accuracy of the cross-section data used for simulating the various interactions between the ionizing radiations and matter.
- How accurately the radiation beams are modeled with respect to energy and angular distribution.
- The statistical accuracy of the Monte Carlo calculation method, which is mainly determined by the number of histories simulated and the consequent implications for simulation time.

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- How the patient geometry and tissue properties are related to the radiation interaction that are modeled.

In this study, MC modeling was used to optimize the MRI-polymer gel dosimetry method. At first, EGSnrc MC simulation dosimetry results for a Co-60 machine were benchmarked through its comparison to “Theratron 80 isodose chart”.

In previous studies (Venning et al., 2005, 2006; De Deene et al., 2006), it has been shown that except the sensitivity, the nPAG gel dosimeter has superior radiation properties as compared to the nMAG gel dosimeter.

Our work revealed the importance of PAGAT polymer gel fabrication method on PAGAT polymer gel performance and also showed the MC simulation as a stand alone method for optimization in gel dosimetry.

2. Materials and methods

2.1. Polymer gel dosimeter preparation

In this study PAGAT polymer gel dosimeter was made according to Venning et al. (2005). All the chemicals used in the study were purchased from Sigma Aldrich, Sydney. The formulation to give the maximum change in the transverse relaxation rate, R2 (1/T2), was determined to be 4.5% *N,N'*-methylene-bis-acrylamide (bis), 4.5% acrylamide (AA), 5% gelatine, 5 mM THPC, 0.01 mM hydroquinone (HQ) and 86% H₂O.

Two methods were used to make the PAGAT gel dosimeter. At first, the Venning et al. (2005) proposed method (method A) was used, in which the gelatine was added to the ultra-pure de-ionized water and left to soak for 10 min, followed by heating to 48 °C using an electrical heating plate controlled by a thermostat. Once the gelatine was completely dissolved the heat was turned off and the cross-linking agent bis was added and stirred until dissolved. Then AA was added and stirred until dissolved, using pipettes the polymerization inhibitor HQ and the THPC anti-oxidant were combined with the polymer gel solution (PAGAT (A)).

In another preparation procedure, De Deene et al. (2006) proposed method was used (method B), in which for the nPAG gels containing crosslinker, the acrylamide and crosslinker *N,N'*-methylene-bis-acrylamide were first dissolved in the 40% total water volume by heating to 45 °C and then the gelatin solution was then cooled down to 35 °C before it was mixed with the monomer solution. The anti-oxidant was added to the solution under heavy stirring just before filling the test tubes (PAGAT (B)).

2.2. Phantom

The phantom in this study (Fig. 1a) was a water filled cubic container (17 × 17 × 12 cm³) and three gel filled cylindrical vials, which in part can be replaced with air and bone equivalent material cubics with dimensions 2 × 2 × 2 cm³ (Fig. 1b). Bone equivalent material was made from poly-tetra-fluoro-ethylene (PTFE) with density of 2.2 gm/cm³.

2.3. Phantom and calibration vials irradiation

Briefly, an external treatment unit (Theratron 80) was chosen as the photon source (source–phantom distance: 80 cm, irradiation field: 10 cm × 10 cm). The source was composed of a Co-60 ($E = 1.17, 1.33$ MeV) cylinder with a diameter of 2 cm and a height of 2 cm.

During irradiation, gel vials were centrally placed inside the container, and 30 Gy was given to depth of 3 cm, leading to the maximum dose of 33.8 Gy for the homogenous phantom. The isodose lines were obtained by normalizing the values to prescribed dose (i.e. 30 Gy at depth of 3 cm for homogeneous phantom).

The calibration tubes were irradiated by the same Theratron Co-60 machine using container in which the calibration vials could be placed horizontally (Fig. 2). The calibration vials were irradiated from 0 to 40 Gy with steps of 2.5 and 5 (i.e. 0, 2.5, 5, 7.5, 10, 15, 20, 25, 30, 35 and 40).

Post-manufacture irradiation time for all above studies was 24 h.

2.4. Polymer gel dosimeter evaluation

The polymer gel dosimeters were imaged using a Siemens 1.5 T clinical MRI scanner in a transmitter/receiver head coil. A multi-echo sequence with 32 echoes was used for the evaluation of irradiated polymer gel dosimeters. The parameters of the sequence were as follows: TR 3000 ms, TE 22–640 ms, slice thickness 1 mm, FOV 128 mm, matrix size 128 × 128, pixel size 1.0 × 1.0 mm², and two acquisitions. The R2 and dose maps were computed using modified radiotherapy gel dosimetry image processing software developed in MatLab.

2.5. Monte Carlo modeling

In this study in order to investigate the accuracy of polymer gel dosimetry, EGSnrcMP simulation code (Kawrakow et al., 2004) was used.

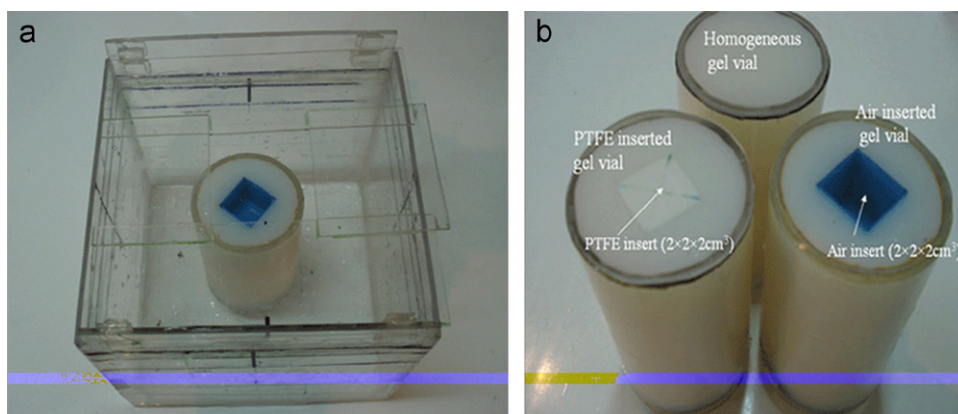


Fig. 1. (a) Cubic water filled phantom for irradiating gel vials, (b) homogeneous, air inserted, and PTFE inserted cylindrical gel filled vials (after irradiation).

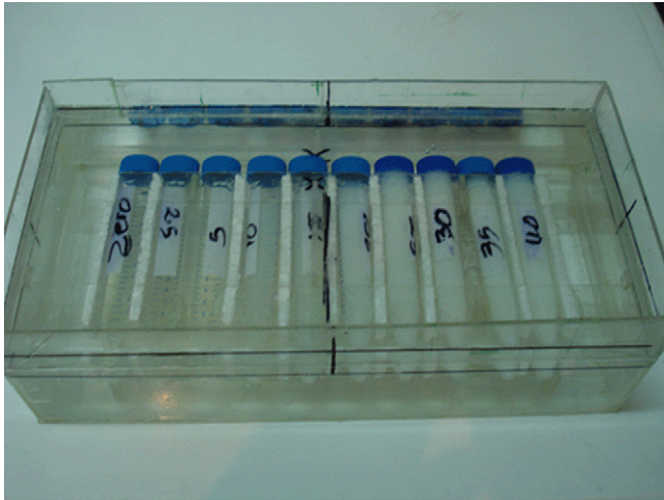


Fig. 2. An especial container for irradiation the calibration tubes.

The validation of a Monte Carlo-based dosimetry was first assessed by “Theratron 80 isodose chart”.

The EGSnrc based MC user code BEAMnrc (Rogers et al., 2007) was used to simulate the head of Co-60 machine geometry, and another general-purpose MC EGSnrc user code DOSXYZnrc (Walters et al., 2007) which considers the phantom divided in a large number of small volume elements, or voxels, was employed to obtain the 3D dose distributions in the phantom.

In the investigation of dose perturbations produced by heterogeneities, MC has showed up as a useful tool, mainly because it accounts, in an adequate way, for the lack of electron equilibrium near interfaces.

The calculation error for homogeneous and inhomogeneous geometries was on average $\pm 2.4\%$ (maximum $\pm 2.7\%$ and minimum 2.3%).

3. Results

3.1. Dose response evaluation

Calibration data for the PAGAT gel batch used in this work were obtained by the analysis of axial T2 maps of the calibration gel tubes 24 h post-irradiation and by fitting cubic and quadratic approximations on R2 values of PAGAT (A) and (B), respectively (Figs. 3 and 4).

Inhibition due to oxygen for doses lower than 5 Gy was observed for both PAGAT (A) and (B), however, for PAGAT (A) inhibition occurred up to 15 Gy.

In doses up to 30 Gy, the dynamic range of PAGAT (A) (2.0 s^{-1}) is lower than PAGAT (B) (2.7 s^{-1}). The values of dynamic range were derived from the formulas of the approximated curves on R2 values (Figs. 3 and 4).

The R2 (0) and dose response of PAGAT (A) from 15–30 Gy were 1.07 s^{-1} and $0.130 \pm 0.004 \text{ s}^{-1} \text{ Gy}^{-1}$, respectively, and of PAGAT (B) were 1.17 s^{-1} and $0.074 \pm 0.004 \text{ s}^{-1} \text{ Gy}^{-1}$, respectively.

The values of R2 (0) were derived from the intercepts of fitting cubic and quadratic approximations to data (Figs. 3 and 4) and dose response within mentioned dose range (i.e. 15–30 Gy) were derived from the slopes of linear regression in data that were averaged for three separate experiments.

Using the same method, dose response was also calculated from 5–15 Gy for PAGAT (B) that was $0.131 \pm 0.003 \text{ s}^{-1} \text{ Gy}^{-1}$ compared with no response for PAGAT (A).

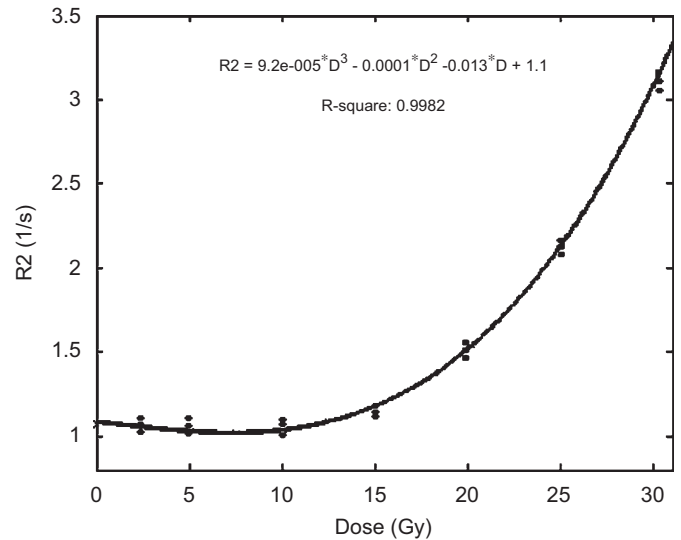


Fig. 3. R2-dose curve obtained for PAGAT (A) polymer gel dosimeter, based on three separate experiments.

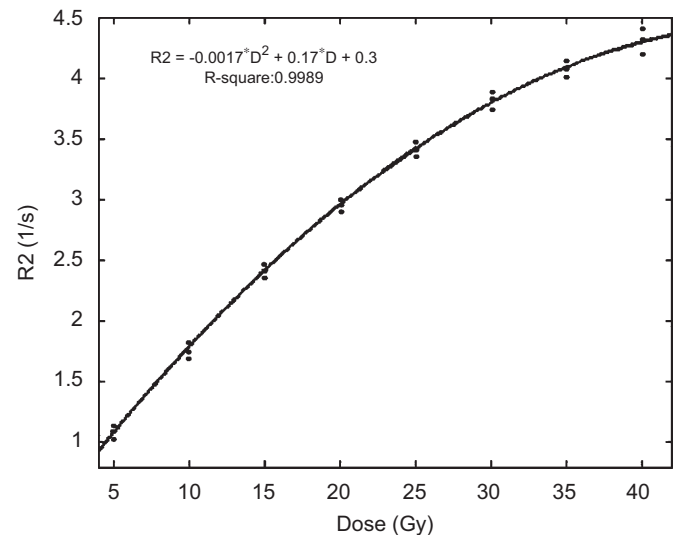


Fig. 4. R2-dose curve obtained for PAGAT (B) polymer gel dosimeter, based on three separate experiments.

In another experiment with method A but 10 times concentration of anti-oxidant (50 mM) and auto-polymerization inhibitor (HQ) no inhibition due to oxygen was observed, but the dynamic range and also dose response from 15–30 Gy (1.33 s^{-1} and $0.037 \pm 0.002 \text{ s}^{-1} \text{ Gy}^{-1}$, respectively) were lower than PAGAT(A) and PAGAT(B) (Fig. 5).

3.2. Dose maps and relative isodose curves of gel vials

After discarding the first echo of the 32-echo train, a single T2 (spin-spin relaxation time) map was automatically derived for each reconstructed slice. These maps were exported from the scanner in DICOM (Version 3.0) format and then imported into the MatLab (MathWorks 2007) to construct a 2D T2 matrix which was subsequently converted to an R2 relaxation rate matrix. Fig. 6 shows the dose maps of PAGAT (B) for both homogeneous and the vials with air and PTFE insert.

For all the above cases we used the same imaging parameters. The PAGAT (B) and (A) gel vials and the calibration tubes were left

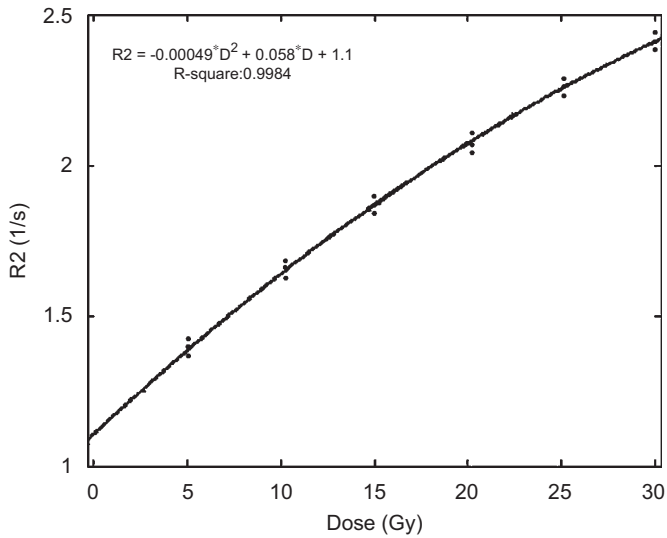


Fig. 5. R2-dose curve obtained for PAGAT polymer gel dosimeter (method A), 50mM THPC and 0.1mM HQ, based on three separate experiments.

in the imaging room for 10h, before imaging, to acclimatize at room temperature (22 °C).

Figs. 7–8 show the relative isodose curves obtained using the MC simulation and PAGAT (B) gel dosimeter. Using the MatLab program (MathWorks 2007) 0.7, 0.8, and 0.9 relative isodose curves were derived from coronal dose maps of central axis in both homogeneous and inhomogeneous gel vials. Fig. 7 also compares the results with the “Theratron 80 isodose chart”.

Comparison of data showed in average 7.3 ± 2.6 , 3.7 ± 2.3 , and 3.0 ± 1.9 mm DTA between the measured and simulated data for 0.7, 0.8, and 0.9 relative isodose lines, respectively, in the homogeneous phantom (Fig. 9).

DTA parameters for the mentioned relative isodoses were compared over the area of X and Z axes along the central axis of gel vials (i.e. 40 mm of X axis and 70 mm of Z axis). This limitation is due to thickness of gel vials’ wall and effect of oxygen at the side of vials’ cap (Fig. 6). Applying this limitation in generating the DTA values helps to lower the errors, whereas, for calculation the dose distribution using simulation such sources of errors (i.e. penetration of oxygen or wall effects) did not exist.

When measured and calculated data in the homogeneous phantom were compared with “Theratron 80 Co-60 isodose

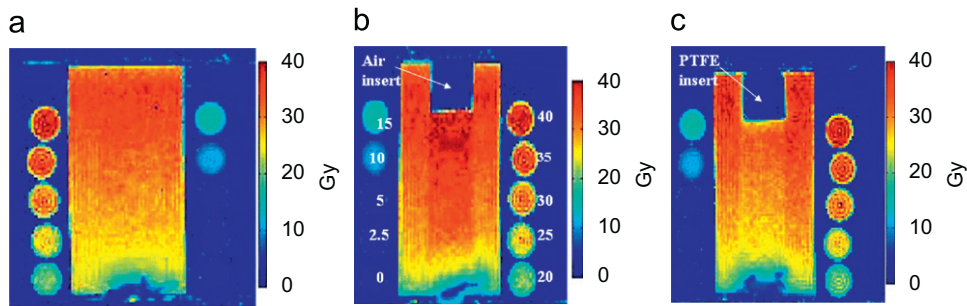


Fig. 6. Coronal T2-weighted MR dose images of the polymer gel in homogeneous gel vial (a), gel vial with air insert (b), and gel vial with PTFE insert (c) for PAGAT (B). Dose maps clearly show the effect of air and PTFE insert on dose distribution.

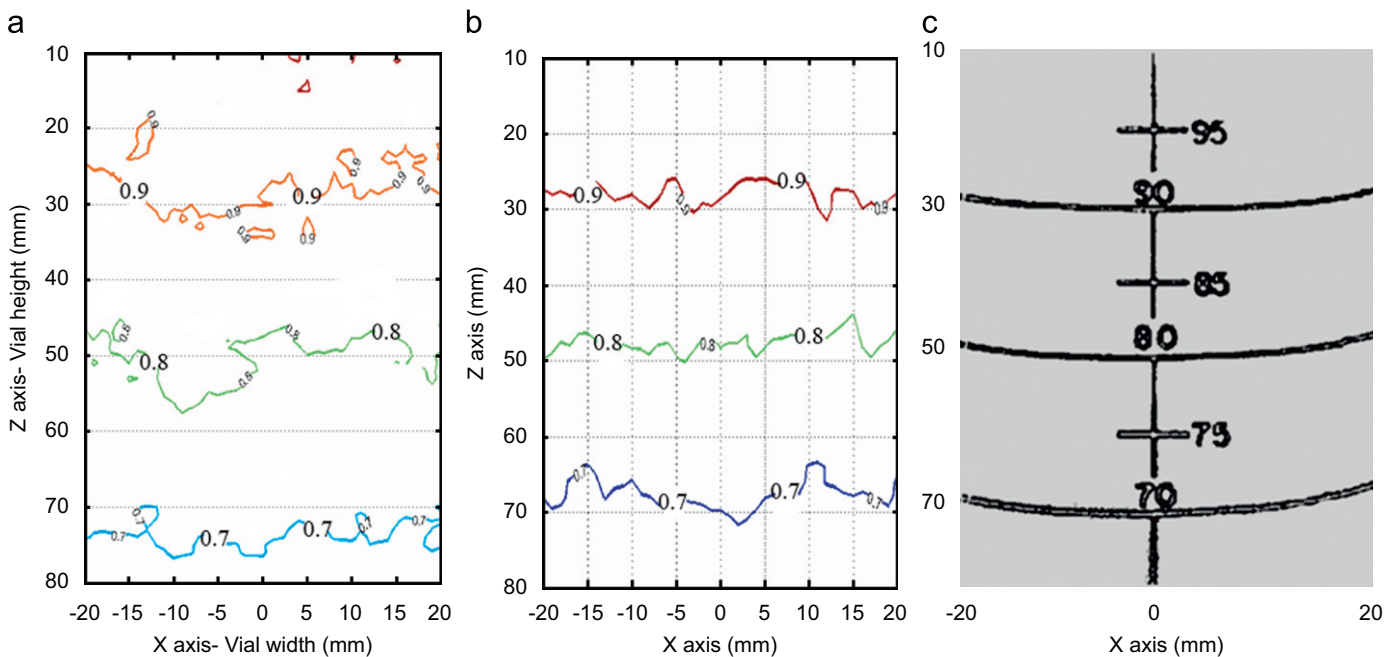


Fig. 7. Relative isodose curves obtained using PAGAT gel dosimeter (a) EGSnrc simulation code (b) and “Theratron 80 Co-60 isodose chart” (c) in homogeneous water phantom on Co-60 machine for 10×10 cm² field over a limited area. DTA for all isodose lines pass the acceptance criteria.

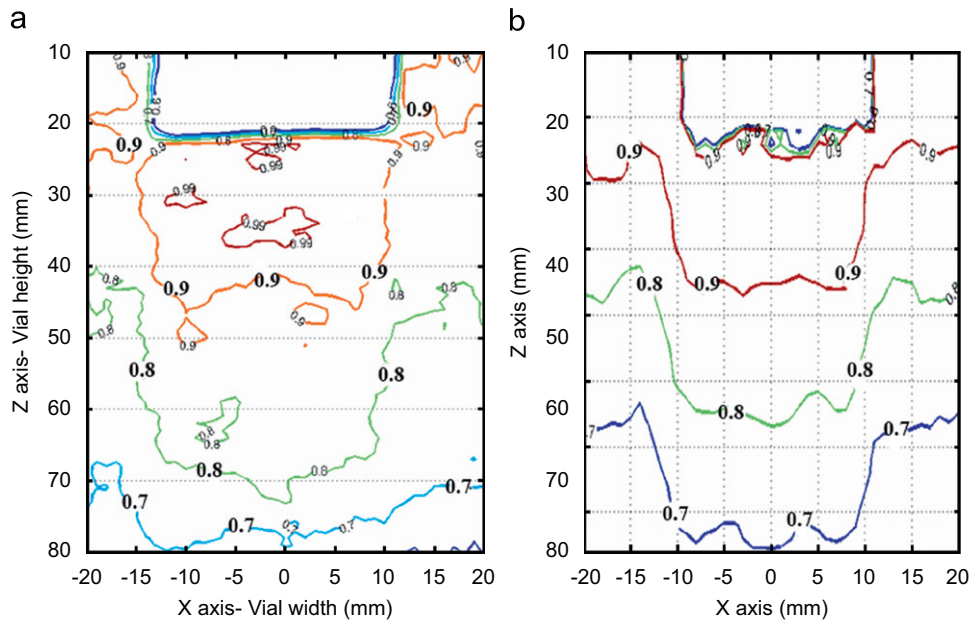


Fig. 8. Relative isodose curves obtained using gel dosimeter (a) and EGSnrc simulation code, (b) in a phantom with air insert on Co-60 machine for $10 \times 10 \text{ cm}^2$ field. DTA for all isodose lines pass the acceptance criteria.

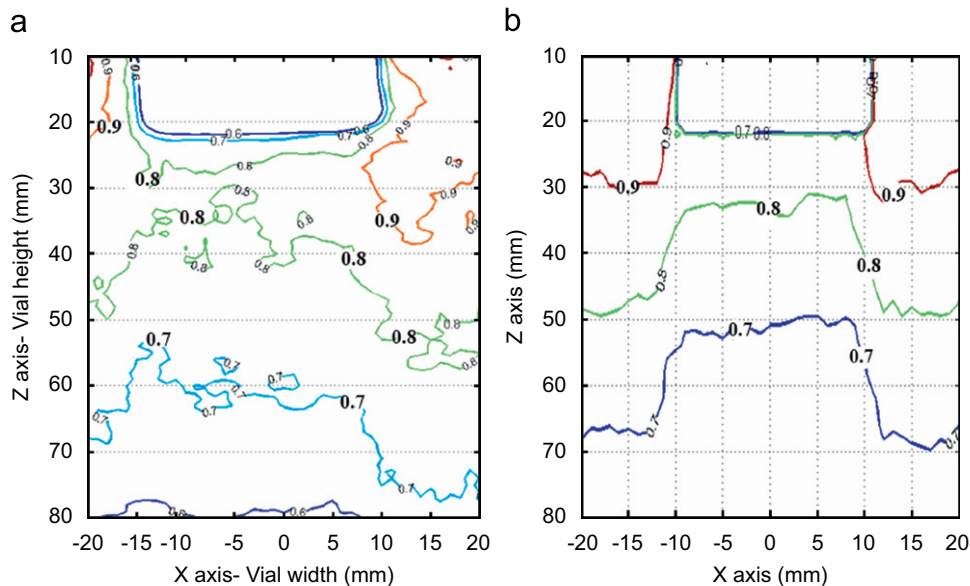


Fig. 9. Relative isodose curves obtained using gel dosimeter (a) and EGSnrc simulation code, (b) in the phantom with PTFE insert on Co-60 machine for $10 \times 10 \text{ cm}^2$ field. DTA for all isodose lines, except 0.7, pass the acceptance criteria.

Chart,” the average DTA for 0.7, 0.8, and 0.9 mm relative isodose lines were 1.2 ± 1.2 , 1.3 ± 1.3 , and 1.8 ± 1.5 , respectively, in comparison with MC results, and 6.3 ± 1.5 , 2.9 ± 2.3 , and 1.3 ± 0.9 , respectively, in comparison with the gel dosimeter results.

The average DTA for 0.7, 0.8 and 0.9 relative isodose lines, between the simulated and air inserted gel dosimeter were 4.4 ± 2.4 , 3.9 ± 2.6 , 2.9 ± 2.5 mm, respectively, and also between simulation and gel dosimeter with the PTFE insert were 8.5 ± 4.2 , 5.8 ± 2.9 , and 2.7 ± 2.1 mm, respectively.

4. Discussion

The DTA is the distance between a measured data point and the nearest point in the calculated dose distribution that exhibits

the same dose. An important benefit of applying this parameter is to find the difference between the calculation and measurement relative to the acceptance tolerance (Low, 1998).

Since the criterion of acceptability for a single field treatment for the dose distribution by conventional radiotherapy within the tumor volume is $\pm 5\%$ (Khan, 2003), or the dose is prescribed to an isodose line with dose heterogeneity of no more than $\pm 5\%$ (Perez et al., 2004), it could be concluded that $\pm 5\%$ variation for selected isodose levels is acceptable. Based on our experiments, DTA for all cases, except one (i.e. MC simulation and gel dosimeter with the PTFE insert for 0.7 relative isodose line which is 8.5 ± 4.2 mm) pass this acceptance criterion (i.e. every 10 mm variation within central plane of “Theratron 80 isodose chart,” at most, alters the relative dose level approximately by 5%).

With respect to DTA values in the case of non-homogeneous gel vials which is comparable to DTA in homogenous vials, results confirm the ability of PAGAT(B) gel dosimeter as a reliable tool for evaluation of dose delivery accuracy in the presence of air and bone inhomogeneities.

Regarding dose response of PAGAT (A) and (B), it can be concluded that the procedure of fabricating considerably affect these variables. Based on our experience (unpublished results), it seems that, high temperature of dissolved gelatine (49 °C) cause some monomers to polymerize and polymerization due to high temperature cause the effect of oxygen inhibition appear in broader range of PAGAT(A) in low doses compared with PAGAT(B).

Fig. 5 shows that the dose response of PAGAT polymer gel dosimeter using method A, but 10 times concentration of THPC and auto-polymerization inhibitor (HQ). In this case, no inhibition due to oxygen in low doses was observed. It could be concluded that the concentration of THPC is effective at scavenging oxygen, but in contrast to other studies of PAGAT polymer gel dosimeter (Venning et al., 2004, 2005) in this case, the dose response is lower and no saturation was observed until 30Gy. The only explanation for this observation may be due to the difference in fabrication procedure; however, these results are somewhat similar to those obtained by Venning et al. (2006).

In comparison, the results of study of Venning et al. (2005), is different (i.e. different response, dynamic range) with PAGAT(A) from those obtained by us. In addition, in spite of approximately same dynamic range and also dose response of PAGAT (B) with results of the work of De Deene et al. (2006), the calibration curve of their study shows no inhibition due to oxygen in low doses. We found no reasonable explanation for these problems; however, it may be due to the applied post-manufacture irradiation and post-irradiation imaging times and also type of instruments and monomer or crosslinker components. More studies may be necessary to answer these questions.

5. Conclusion

Experimental results of this work were compared with the corresponding MC calculations and indicate that MC is able to provide accurate dosimetry, free of volume averaging and positioning uncertainties.

Regarding the results obtained using PAGAT (B) in homogeneous and heterogeneous gel vials in comparison with MC simulation, the PAGAT (B) polymer gel formulation investigated in this study exhibited the essential characteristics required for clinical radiotherapy dosimetry for doses from 5 to 40 Gy, and, however, for low doses up to 5 Gy, formulation with higher

concentration of anti-oxidant is required. Altogether, PAGAT polymer gels offer simpler preparation steps and, therefore, would allow easier implementation of it into the routine clinical radiotherapy environment.

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