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Evaluation of CT based MAGAT gel dosimetry system for measuring 3D dose distribution

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ABSTRACT

Background: Polymer gel dosimetry showed the ability to measure three dimensional dose distribution of radiation treatment. The challenge in gel dosimetry is to extract dose information from the irradiated gel dosimeter through medical imaging techniques such as MRI (Magnetic Resonance Image), Ultrasound, Optical CT, Raman Spectroscopy and CT (Computed Tomography) Imaging. **Objective:** The aim of this work is to evaluate the three dimension dose distribution measured using CT based MAGAT (methacrylic acid, gelatine and THP) gel dosimetry in radiation treatment and compare it with Monte Carlo simulation. **Results:** The qualitative comparison of dose distribution for the three fields technique measured using gel dosimetry agreed very well with that calculated using Monte Carlo simulation, with maximum disagreement of 4 mm. **Conclusion:** The Monte Carlo simulation verified that the CT based normoxic gel dosimeter showed to be a great promising method for verifying 3D dose distribution.

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INTRODUCTION

The advances in radiotherapy treatment techniques such as conformal radiotherapy enable radiation treatments to be fitted to the tumor shape. The treatment outcomes can be enhanced using this technique due to an increased the absorbed dose to the tumor while reduced the dose to the surrounded healthy tissue. However, these treatment techniques place considerable demand on dosimetry techniques due to the complex nature of the radiation dose distributions used.

To verify these complex dose distributions before treatment starts three-dimensional (3D) dosimetry system is needed. Dosimeters currently in use, such as ionization chambers and thermoluminescent (TLD) dosimeters, have limitations as they only measure the dose at a single point, and radiographic films only measure a 2D dose distribution. Polymer gel dosimetry showed the ability to measure the three dimensional dose distribution of radiation treatment (Baldock *et al*., 2010; Doran, 2009).

The earlier types of polymer gel dosimetry use in the clinic have been limited due to the long and difficult procedure of avoiding oxygen to penetrate the gel during preparation process. Oxygen is an efficient scavenger of free radicals which leads to inhibit the polymerisation process (De Deene *et al*., 2001; Salomons *et al*., 2002).

A new polymer gel formulation which contains oxygen scavengers and can be prepared in normal atmospheric conditions was reported called MAGIC gel (Fong *et al*., 2001). Subsequently, De Deene *et al*. (2002a) investigated various oxygen scavengers and it was found that tetrakis (hydroxymethyl) phosphonium chloride (THP) was effective at scavenging oxygen. THP was used to replace ascorbic acid and copper sulphate in the MAGIC formulation and a new formulation consisting of methacrylic acid, gelatine and THP, named MAGAT was proposed (De Deene *et al*., 2002a). Other normoxic gel formulations were also developed such as MAGAS (methacrylic acid gelatine and ascorbic acid), and PAGAS (polyacrylamide gel and ascorbic acid) gels (De Deene *et al*., 2002a; De Deene *et al*., 2002b). A work of different compositions of normoxic polymer gel dosimeters have been summarized by Baldock's study (Baldock *et al*., 2010).

Number of methods have been proposed to read dose information in gel dosimetry such as magnetic resonance imaging (Maryanski *et al*., 1993), Fourier-Transform Raman Spectroscopy (Baldock *et al*., 1998), Optical Computed Tomography (Oldham *et al*., 2008; Oldham *et al*., 2003; Oldham *et al*., 2001; Wai *et al*., 2009),Ultrasound (Mather *et al*., 2002), and X-ray Computed Tomography (Hilts *et al*., 2000).

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The most method of choice to read dose information in gel dosimeter has been magnetic resonance imaging (Amin *et al*., 2004; Buckley *et al*., 2003; De Deene *et al*., 2002a; De Deene *et al*., 2002b; Fong *et al*., 2001; Gear *et al*., 2006; Gustavsson *et al*., 2003; Scheib *et al*., 2004). However, this technique showed some limitations such as change of temperature of gel dosimeter during imaging process which can lead to a change in spin-spin relaxation time (T2) (De Deene and De Wagter, 1999). Also, the lengthy imaging times and the restricted access of MRI scanners to radiotherapy clinics are included in the current limitations of MRI imaging (Oldham *et al*., 2001). The advantages of CT scanner among other methods to read the dose are: availability of CT to clinical radiation therapy for treatment planning purposes, simplicity & rapidity of image acquisition, and relatively insensitive to environmental factors.

The aim of this work is to study the capability of CT based MAGAT normoxic gel dosimetry to measure dose distribution and to verify the measured dose distribution using Monte Carlo simulation. Which is a very important step towards making MAGAT gel dosimetry a standard tool for verification of three dimensional dose distribution.

METHODS AND MATERIALS

Gel preparation:

The MAGAT (Methacrylic Acid, Gelatin and Tetrakis (hydroxymethyl) phosphonium chloride) gel was prepared based on a method proposed in the literature by De Deene *et al*. (2002a). The chemical materials used to produce MAGAT gel were 9% Methacrylic acid, 8% Gelatin type A (300 bloom), 0.19% Tetrakis (hydroxymethyl) phosphonium chloride (THP) and 83% deionised water. The prepared gel was poured into a set of plastic containers (diameter 2.4 cm, height 7 cm) for gel calibration. A 2.7 liter volume of MAGAT gel dosimeter was also prepared and poured into a big plastic container (14 cm x 14 cm x 14 cm) for dose distribution measurement. The samples were filled up to the top to avoid oxygen entering the gel from the air space above the gel and sealed with plastic lids then stored at 4°C in refrigerator.

Gel irradiation:

For calibration purposes, the gel in plastic containers was irradiated to different doses at a dose rate of 300 cGy per minute using 6 MV photon beam from linear accelerator (Siemens Primus, USA). The time between gel preparation and irradiation was about 24 hours. The containers were arranged in a rectangle holder made out of perspex to be used during irradiation. The samples on the perspex holder were placed verticaly in a water bath to provide full scattering during irradiation. The samples were placed at dmax inside the water phantom. One of the sample was kept unirradiated as a control. The samples were irradiated using 17 cm x 10 cm field size with source to surface distance (SSD = 100 cm) at tempreture 23°C. The samples were irradiated to dose range of 2 Gy to 30 Gy. For dose distribution measurement, a 2.5 L volume of gel dosimeter was irradiated using 6 MV photon beam from linear accelerator (Siemens Primus, USA) with total dose of 12 Gy. The irradiation procedure was based on typical treatment setup for prostate cancer patient with three irregular field sizes.

CT imaging:

The irradiated sample inside cylindrical Perspex phantom filled with water was scanned using diagnostic CT scanner (Siemens Medical Solution, Malvern, USA), 48 hours after irradiation to ensure the polymerisation process was completed. Scanning parameters chosen were: 140 kV, 400 mAs, and 3 mm slice thickness. All images were obtained when the scanner was fully warmed up in order to reduce uncertainty in the CT number to dose response (Hilts *et al*., 2000). The gel dosimeter was scanned 20 times for image averaging process. OsiriX imaging software was used to save CT images in DICOM format to be analyzed in personal computer. The ImageJ (developed at the US National institutes of health) was used to process the data for absorbed dose calibration and dose distribution measurement. The pixel value was measured over a region of interest chosen, then plotted against the known dose to obtain the calibration curve. The dose distribution in the calibrated big gel dosimeter was measured.

Monte Carlo simulation:

The Monte Carlo simulation was carried out using BEAMnrc and DOSXYZnrc codes to perform all dose calculation (Kawrakow *et al*., 2009). The Monte Carlo simulations were run using a computer with Intel (R) Xenon processor of 2.2 GHz speed. Primus Linear accelerator head geometry (Siemens Primus, USA) was modeled using BEAMnrc program to carry out Monte Carlo simulation (Aljamal and Zakaria, 2013). The primary output of the BEAMnrc simulation for the head of linear accelerator is a file called phase space file which has information about all the particles leaving the accelerator. The position of the jaws and MLC in the linear accelerator head simulation was set based on treatment setup. Three phase space files were created separately using BEAMnrc simulation. Each phase space file has different field size (irregular shape). A total of 2×10^6 histories were run in the accelerator head calculations. The electron cut-off energy (ECUT) was set to

0.7 MeV while the photon cut-off energy (PCUT) was set to 0.01 MeV (Ceberg *et al*., 2010). The Directional bremsstrahlung splitting (DBS) option was used in all simulation. The CT scan images of unirradiated gel mentioned were used to create the gel phantom. CTCREATE utility used to extract CT data from DICOM files of the unirradiated gel and to create the *.egsphant file. This file was used as input file in DOSXYZnrc simulation. The phase space files created by BEAMnrc were scored in the center of gel phantom from three different directions (Anterior, right lateral and Oblique). A total of 2 x 10^9 histories were run in the simulation. The DOSXYZ_SHOW software was used to display the dose distribution in the gel phantom. The dose distribution in the simulated gel phantoms were compared with that measured in gel dosimetry.

RESULTS AND DISCUSSION

The variation in the pixel intensity of the irradiated samples with dose is shown in Fig. 1. Very good correlation (r=0.919) between average CT number and dose was found. A linear relationship between pixel intensity and absorbed dose was observed up to 18 Gy with CT number-dose sensitivity of 0.88 ± 0.02 HU Gy^{-1}. The increase in pixel intensity values with absorbed dose was due to an increase in the linear attenuation coefficient relative to that of water because of the radiation-induced polymerisation of methacrylic acid. It was also found that the dose sensitivity was decreased after the linear region due to the polymerisation of methacrylic acid tended to saturate at high dose regions. Brindha *et al*. (2004) found that there was a linear relationship between average CT number and absorbed dose for MAGAT gel up to 10 Gy with CT number-dose sensitivity to be 0.85 ± 0.08 HU Gy^{-1} (Brindha *et al*., 2004). In the current study, the CT number-dose sensitivity was higher by 0.03 HU Gy^{-1} than that of the study done by Brindha *et al*. (2004) and the linear region was higher as well. These differences could be attributed to the differences in impurity of main materials that were used in preparation of MAGAT gel and the differences in model of the CT scanner.

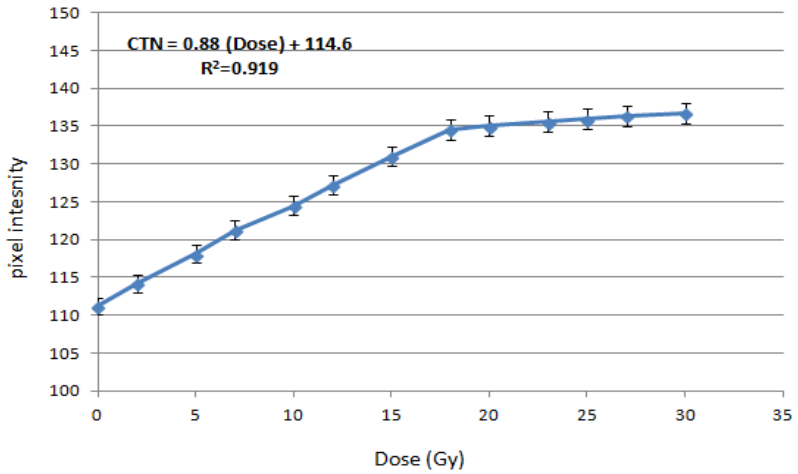

Fig. 1: The pixel intensity versus dose for irradiated gel

Monte Carlo simulation can be considered as the most accurate method to calculate the dose distribution in different radiotherapy treatment applications. To verify the 3D dose distribution measured using gel dosimetry, a comparison of dose distribution obtained by Monte Carlo simulation and gel dosimetry measurement was made as shown in Fig. 2.

The spatial distribution of the absorbed dose for the measured gel dosimetry was in close agreement with that calculated using Monte Carlo simulation. It was also observed that the measured isodose lines compare favourably with the calculated isodose lines. For the isodoses lines ≥ 60%, the maximum deviation between the measured and calculated isodose lines was found to be 4 mm. This deviation between measured and calculated isodose lines could be attributed to voxel size that used to create MAGAT gel phantom using Monte Carlo simulation. The size of the voxel determines the resolution of a particular dose distribution. High resolution dose distribution is achieved by decreasing the voxel size. The voxel size used in the simulation had a dimension of 0.5 cm in the XY axis. The number of voxels that could be defined in XY axis was 28 voxels only while, in Z axis was 56 voxels. This limitation in size and number of the voxel has a dramatic effect on the calculation accuracy in Monte Carlo method and lead to decrease the resolution of the dose distribution. This limitation could be the main reason for the small deviation between measured and calculated isodoses lines. Also, the random error that results during the simulation could be another reason for the deviation which can be seen clearly at the lower region of 50% isodose line. For the 40% isodose line, the calculated and measured dose distribution agreed very well within 0-4 mm. A large individual point fluctuation can be observed at 20%

isodose line due to the low dose gradient at this area and the effect of imaging filtering on CT gel images. The Mean filter was used in the current study to reduce the artefact in CT gel images. The Mean image filter provides the best noise reduction but an unacceptable degradation in spatial dose information (Hilts and Duzenli, 2003), which can be seen clearly in the current study at 20% isodose lines, where the spatial information of the gel dosimetry image was effected significantly at low dose regions.

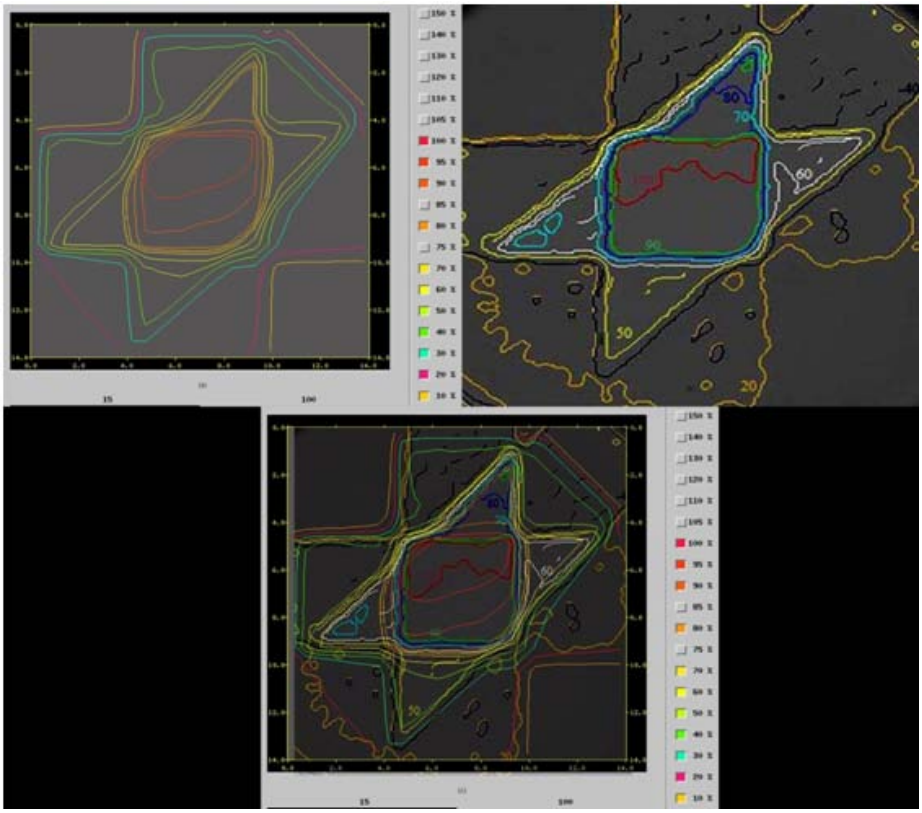

Fig. 2: The dose distribution by MC calculation (upper left), gel dosimetry measurement (upper right), and comparison between MC and gel dosimetry dose distribution (down picture)

Conclusion:

Monte Carlo simulation method was used to verify the ability of CT based gel dosimetry system to measure dose distribution. The dose distribution measured from gel dosimetry was compared with that calculated using Monte Carlo simulation. The quantitative comparison of dose distribution for the prostate cancer treatment measured using gel dosimetry showed very good agreements with that calculated using Monte Carlo simulation, with maximum disagreement of 4 mm. However, the difference was found the highest at 20% isodose line due to the low dose gradient. In conclusion, the polymer gel dosimeter in combination with CT imaging has been shown to be a valuable device for verifying three-dimensional dose distribution.

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