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Small field size dose-profile measurements using gel dosimeters, gafchromic films and micro-thermoluminescent dosimeters

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ABSTRACT

The introduction of mini-multi-leaf collimators (MMLC) into radiotherapy has seen the use of smaller field sizes become increasingly important. Small field sizes that tightly conform to precise target regions are sought in radiotherapy to deliver doses with a high therapeutic ratio. MMLCs have made it possible to shrink field sizes in radiotherapy to below half a centimetre. The dosimetry of such fields with conventional dosimeters such as gas-ionisation chambers is not feasible due to limitations caused by the chambers relatively large size compared to the size of the collimated beam. In this work, the dose distribution of radiotherapy beams collimated to such small sizes were examined using polyacrylamide gels dosimeters, Gafchromic films and micro-thermoluminescence dosimeters (micro-TLDs). Dose penumbra widths obtained with gel dosimeters, Gafchormic film and micro-TLDs were generally in agreement with each other, although a wider FWHM of the field was measured with gel in comparison to film. An asymmetric dose distribution between the two axis profiles of a 3×3 mm collimated field was observed and can be attributed to an inherent asymmetry of the MMLC.

1. Introduction

Radiotherapy techniques are continuously employing smaller and smaller field sizes to deliver tighter radiation doses with higher therapeutic ratios, generating interest among researchers to provide reliable dosimetry for beams and treatment plans collimated to small field sizes (Francescon et al., 1998; Pappas et al., 2001; Laub and Wong, 2003; Sohn et al., 2003; Lee et al., 2006; Pappas et al., 2006; Wong et al., 2007, Pappas et al., 2008). Recently, research into field sizes of sub-centimetre dimensions has been investigated in radiotherapy particularly with mini-multi-leaf collimators (MMLCs) (Sohn et al., 2003; Zhu et al., 2003; Wang et al., 2004). Dosimetry and calibrations are usually performed for field sizes around 10×10 cm. It is also known that the depth distribution will vary with field size (Sohn et al., 2003) and that for small field sizes a relatively large part will be the penumbra region (Khan, 2003). The dosimetry of small field sizes presents a challenge to the most commonly used dosimeters in radiotherapy, gas-ionisation chambers. Due to the relatively large sizes of ionisation chambers (Low et al., 2003) (minimum in the range of 10 mm^3) compared to such small field sizes causing volume average effects (Higgins et al., 1995; Duggan and Coffey, 1998; Low et al., 2003) and the lack of charge equilibrium under such circumstances (Duggan and Coffey, 1998; Low et al., 2003), therefore ionisation chambers cannot reliably measure the dose distribution of beams that have been collimated into such small fields. However, recently McKerracher et al. have shown that lateral electronic equilibrium is not necessary for determining scatter parameters for such small field sizes nor is electron contamination a problem (McKerracher and Thwaites, 2007a, b).

A method of dose measurement that is not limited in this way is polymer gel dosimetry which was first demonstrated in 1993 (Maryanski et al., 1993). Incident radiation creates free radicals in the gel, causing the monomer to be transformed into a polymer (McJury et al., 2000). Gels allow the measurement of the energy deposited from a source of radiation to be measured in a 3 dimensional volume and the resolution will be limited by the resolving power of the scanning technique. The type of gel used in

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this work focuses on using acrylamide and BIS transformed into polyacrylamide, as developed by Maryanski et al., 1994. Gels are tissue-equivalent (De Deene, 2004), their response to radiation is relatively energy independent (De Deene, 2004) and the dose distribution in these gels can be determined by several methods. A common method of gel polymerisation measurement that is used in this work is MRI, others include X-ray and light CT, and Raman spectroscopy. When using MRI, the smallest unit of volume that can be measured (voxel size) will typically be in the sub-millimetre range. In this work, a 7 T MRI scanner was used with a small core (1.5 cm diameter), as the higher than standard magnetic field strength (1.5 T) and magnetic gradients should improve the level of resolution that can be obtained (Berg et al., 2001; Hurley et al., 2003). This has rendered the dose distribution determination within gels to be within a small fraction of a millimetre.

Another method of measuring the dose distribution from ionising radiation that is commonly used in radiotherapy is by using Gafchromic film. Its exposure to radiation causes the film to darken blue in proportion, and the degree to which the Gafchromic film's transparency is reduced is used to determine the incident dose (Francescon et al., 1998). Gafchromic film is a self-developing medium that is relatively energy independent (Butson et al., 1998), dose rate independent (Niroomand-Rad et al., 1998) and has a high intrinsic resolution (>1200 lines/mm) (McLaughlin et al., 1991). One noted disadvantage of these films in comparison to gel dosimetry is that they can only measure dose distributions in a 2D plane.

Special type Thermoluminescent Dosimeters (TLDs) can also be used for dosimetry of small fields. TLDs are small crystals whose structure is altered by irradiation. Applying heat will repair the crystal, causing it to emit light in proportion to the initial level of radiation and allowing it to be used as a method of dosimetry (Taylor and Lilley, 1978). They can be placed in a field to measure the dose distribution by measuring it on a point-by-point basis. Micro-TLDs (made from Lithium Fluoride in this work) can be used to determine dose in a region based on this size ($1 \times 1 \times 1$ mm^3) and several micro-TLDs placed throughout the field can be used to determine the dose distribution. The size of micro-TLDs is a limitation on their accuracy in situations where the dose can vary quickly between regions separated by only short distances.

A variety of methods have been employed as researchers quantify the dose distribution of beams collimated to increasingly tighter field sizes (Francescon et al., 1998; Laub and Wong, 2003; Sohn et al., 2003; Pappas et al., 2006; Wong et al., 2007, Pappas et al., 2008). This work continues on in this direction to quantify beams collimated to 3×3 mm and 4 mm diameters circular fields, using polymerising gel, radiochromic film and micro-TLDs. Intercomparison of these methods show that for normalised measurements, gel, radiochromic film and micro-TLDs give similar shapes to the curve, with some variation within the extent of the penumbra.

2. Method

In this section we describe the preparation and use of gel dosimeters, Gahchromic films and micro-TLDs as applied to the measurement of tightly collimated fields, followed by a description of the analysis techniques employed.

2.1. Gel preparation

Gel samples were prepared using PAGAT gel (Polyacrylamide, gelatine and THP) type (Venning et al., 2004; Venning et al., 2005). This polymer gel is comprised of acrylamide (3% of total mass), N' N-methylene-bis-acrylamide (BIS) (3% of total mass), gelatine (5% of total mass) and the remaining mass of the solution being de-ionised water (89% of total mass). To overcome the problems associated with oxygen in the solution preventing polymerisation in normal PAG gels (McJury et al., 2000; Maryanski et al., 1994), PAGAT uses Tetrakis (hydromethyl) phosphonium chloride (THPC) to consume the oxygen (in this work a concentration of 5 mmol L^{-1} was used). These gels were prepared by heating the de-ionised water to approximately 45 °C, and then each of the components was added and dissolved into the solution. The solution was allowed to cool to 35 °C and then THPC was mixed into the solution. A pipette was used to place the gel solution into separate vials and these were then sealed in preparation for irradiation. All vials were filled with gel produced from a single batch to avoid the known problem of variation between batches of gel (De Deene, 2004).

Before irradiation, the vials were kept in a sealed argon-filled flask to minimise the possibility of any additional atmospheric oxygen from entering the vials. Vials used in this work were made from Pyrex glass (Pyrex disposable culture tubes, Sigma Aldrich), and are 100 mm long and have an outer diameter of 13 mm. They have a screw cap allowing them to be filled and sealed without an air gap. The tight diameter of the vial is a requirement for the vial to be used in the desired 7 T MRI coil, which has an inner diameter of 15 mm. After preparation and prior to irradiation, the gel dosimeter samples were observed to be clear.

2.2. Gel irradiation

Irradiation was performed using a Varian 600C linear accelerator, delivering a 6 MV beam at a dose rate of 250 MU min^{-1}. The linear accelerator was previously calibrated according to the IAEA TRS398 protocol, with local policy implementing a 2% action limit for recalibration, thus doses were delivered with an uncertainty of 2%. Gel dosimeter samples were placed into water at a depth of 5 cm and a distance of 95 cm from water surface to linac target. For calibration, samples were irradiated with a 9.8×9.8 cm field size, under which 100 monitor units (MU) is equivalent to 1 Gy. Gel calibration samples were irradiated at 0 (control), 1, 3, 5, 10, 15, 20 and 30 Gy.

In this work, two tightly collimated beam setups were employed. The first used the MMLC to collimate the beam to a field size of 3×3 mm and set to deliver 3000 MU, which was estimated beforehand to be approximately 10 Gy. The second used a 4 mm diameter circular collimator and a dose of 2250 MU, calculated to be equivalent to 13.16 Gy. The main jaws of the linear accelerator were set to 6×6 cm wide before the collimation by the 4 mm circular collimator and 1×1 cm before collimation by the MMLC to 3×3 mm.

2.3. Gel scanning

Gel samples were scanned using a 7 T MRI scanner (Bruker Advance 300 MR micro-imaging system). For calibration samples, fast settings (64×64 matrix, TE = 5.000 ms, TR = 6.000 s, 1 average, scan time 6 min 24 s, slice 6 mm thick, 256 echoes, pixel size = 219 μm) were employed, the calibration data used to determine how close to linear the gel response was. In addition, imaging of gels irradiated by small fields had altered imaging sequences to more accurately determine the shape of the profile. In these cases it should be noted that the scanning parameters will influence the measured T_2 values (Hurley et al., 2003). Images of the polymer gel irradiated by a 4 mm circular beam were also scanned at a high resolution (128×128 pixels over 12×12 mm field of view for a pixel size of 94 μm, TE = 5.000 ms, TR = 5.000 s, 4 averages, 1 mm slice thickness, 256 echoes, scan time of 42 min 40 s, repeated 3 times). Image of the polymer gel irradiated by a 3×3 mm were scanned with a sequence similar to the calibration data set (64×64