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Noramaliza M. Noor, M. Hussein, D.A. Bradley, A. Nisbet

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The Potential of Ge-Doped Optical Fibre TL Dosimetry for 3D Verification of High Energy IMRT Photon Beams

Noramaliza M.Noor ^{1*}, M Hussein ², D.A. Bradley ¹ and A. Nisbet ^{1,2}

¹ *Centre for Nuclear and Radiation Physics, Department of Physics, University of Surrey, Guildford, GU2 7XH, UK*

² *Department of Medical Physics, St Luke's Cancer Centre, The Royal Surrey County Hospital NHS Trust, Edgerton Road, Guildford, GU2 7XX, UK*

**Author for correspondence: n.mohdnoor@surrey.ac.uk*

Abstract

Intensity Modulated Radiation Therapy (IMRT) is a technique widely used in the treatment of patients with prostate cancer, the most commonly occurring male cancer in the United States and Western Europe. The technique has many attractive features, promising improved radiotherapy over that provided by conventional techniques, including enabling the tumour to be treated with a uniform high dose, capability for shaping the radiation beams to match the shape of the tumour and potentially improving patient outcome. However, there are a number of concerns involving high photon energy IMRT (>10 MV), including greater radiation leakage and the possibility of photo-neutron production. The aim of the present study is to investigate the potential of Ge-doped optical fibre thermoluminescent (TL) dosimetry in determining typical out-of-field doses for high energy IMRT. Commercial Ge-doped optical fibres have been employed as the TL dosimeters, offering features such as high sensitivity, cost-effectiveness and small size. Extensive measurements have been made, examining reproducibility, sensitivity, energy response and linearity with dose. Screening for sensitivity to dose of the individual fibres and subsequent selection has led to an overall coefficient of variation (CV) of better than 4 %. Use has been made of an anthropomorphic phantom (RANDO) for photon irradiation measurements delivered over the range of nominal energies 6 – 15 MV as typically used in IMRT treatment of prostate cancer. Comparison has been made with TLD-100 measurements, the latter being corrected at 15 MV for their response to thermal neutrons. The study has demonstrated the Ge-doped optical fibre thermoluminescent (TL) dosimeters to offer good potential for use in IMRT radiotherapy when using 6 MV photons, also indicating a need to correct their response to neutrons when conducting 15MV irradiations.

Keywords: *IMRT, Ge-doped optical fibres, RANDO phantom, TLD-100 and TLD-700*

INTRODUCTION

Advanced delivery techniques in radiotherapy such as IMRT have developed rapidly. However, despite the increased dosimetric benefits of IMRT there are still concerns with regard to the use of IMRT due to the increased number of monitor units required and the potential for secondary cancer induction [1]. This is particularly true for high photon energy (>10 MV) IMRT where photo-neutron production becomes a reality [2]. The issue becomes of increased concern for out-of-field irradiations, where for photon energies > 10 MV, the relative contribution of neutron dose to the overall dose increases. Thus for instance, measurements of the photon dose component far from the treatment field, determined by TLD-100, have been observed to be highly inaccurate at 18 MV [3].

In radiotherapy treatment, it is crucial to verify the dose distribution before any treatment, due to the possible biological complications of the dose delivered. Moreover, it would also be

impractical to measure dose distribution directly in patients treated with radiation. Therefore there is a need for dosimetry systems which offer features that may accurately verify the delivered dose to the patient. These include high spatial resolution, accurate and precise dose measurement and tissue equivalence. This study investigates the potential of Ge-doped optical fibre. For TL measurements it has been previously established that the use of Ge-doped optical fibre offers superior performance to other types of commercially produced optical fibre, providing in particular a wide range of dose sensitivity. Other factors that favour use of optical fibres for radiation dosimetry include their small physical size, the absence of cables and associated high voltages and the capability to provide excellent TLD characteristics [4]. The Ge-doped fibre TL system is compared with the more commonly used lithium fluoride material, TLD-100. TLD-100 has a ^6Li content of 7.5% and a ^7Li content of 92.5 % whereas the more expensive TLD-700 has respective contents of 0.01% and 99.99 %. As ^6Li has a high thermal neutron cross section its use in higher energy beams is limited but TLD-100 could be used if suitable corrections were to be made for neutron dose [5].

MATERIALS AND METHODS

2.1 Ge-doped Optical fibres

Use has been made of single mode commercial Ge-doped silica glass optical fibres (INOCORP, Canada) with a core diameter of 9 μm and a cladding diameter of $116 \pm 0.1 \mu\text{m}$. There are four essential steps in preparing the optical fibres prior to irradiation. This includes removal of the outer polymer of the fibre, cleansing of the residual fibre with methyl alcohol, cutting the fibre into convenient lengths to form individual dosimeters (6mm long strands in the present case) and annealing. A detailed description of the procedure is given by Hashim et al. [6].

2.1.1 Screening process

Prior to use in clinical applications each batch should be screened to ensure the selection of dosimeters having approximately equal mass, length and sensitivity, discarding strands which do not conform to the prescribed dimensions or that have sensitivity outside a defined range of the mean [7]. For this purpose, each batch of optical fibres was irradiated to a photon component of dose of 3 Gy using a 15 MV photon beam delivering dose at the rate of 400 cGy/min; a focus to surface distance (FSD) of 100 cm and $10 \times 10 \text{ cm}^2$ field size were also used in delivering these irradiations. After irradiation the optical fibres were kept in a light-tight box for 12 hours to allow uniform control of thermal fading prior to read out of the TL yield using a Solaro TL reader (Vinten TLD, Reading UK). Finally, a distribution of TL yield (corrected counts per second per unit mass of fibre) against the complete set of irradiated optical fibres was produced and analysed. A limit of 4 % in the coefficient of variation (CV) was applied in carrying out the selection process. The CV was observed to be 33.8 % prior to the selection, decreasing to 3.96 % after selection (Figures 1 and 2). A total of 500 fibres were eventually produced as a result of such screening to allow for the investigations reported below.

Figure 1. Prior to sensitivity selection the coefficient of variation (CV) of fibres was found to be 33.8 %. A total of 407 fibres were irradiated in the run that is represented by the present set of data.

Figure 2. Subsequent to sensitivity selection the coefficient of variation (CV) of fibres was found to be 3.96 %. Following selection, a total of 135 fibres were left from the original number of 407.

2.2 TLD-100

To allow comparison of the Ge-doped optical fibres against a better established TL system, use has been made of TLD-100 chips and disks. The chips were of dimension $3.2 \times 3.2 \times 0.89$ mm while the disks were of 4.5 mm diameter $\times$ 0.89 mm thick, all calibrated against a Farmer-type ionisation chamber. The TLDs were read-out using a QADOS Harshaw 5500 reader with pre-heat at 145 °C for 10 seconds and a temperature ramp of 17 °C per second up to a maximum temperature of 300 °C for 10 seconds. The response of these to neutrons resulting from 15 MV x-ray irradiation was corrected using the results of Kry et al [5], the latter comparing TLD-100 with TLD-700.

2.3 Ge-doped dose calibration

Dose calibration was performed by irradiating the selected Ge-doped optical fibres with 6 MV and 15 MV energy photon beams (using a Varian Linear accelerator and 100 cm FSD, 10×10 cm² field size) at 400 cGy/min dose-rate. The fibres were irradiated with doses ranging from 0.2 cGy up to 100 cGy. A linear relationship between TL-yields and dose (cGy) for both 6 MV and 15 MV energies was observed (Fig 3).

Figure 3. Calibration curve for Ge-doped optical fibres for 6 MV (left hand graph) and 15 MV (right hand graph) photon beam irradiations.

2.4 Alderson RANDO anthropomorphic phantom and measurements

For this project, use was made of a RANDO phantom (The Phantom Laboratory, Salem, NY) version ARTF 1025, with height 1.55 m, weight 50 kg and transverse sections (of which there are 31 in all) 2.5 cm thick, each section containing a matrix of 5 mm diameter holes, depth 2.5 cm, spaced at 1.5 cm $\times$ 1.5 cm to accommodate tissue-equivalent and lung tissue-equivalent plugs. The plugs can be replaced by TLD-100 and Ge-doped optical fibre holders (Figure 4a). Measurements were made as a function of distance along the z-axis of the phantom, away from the Planning Target Volume (PTV), the latter being understood to be located about the central axis of the beam. For a detailed definition of PTV see ICRU Report 62 [8].

2.5 Treatment planning and irradiation

Individual IMRT verification plans were produced for the RANDO phantom, based on data from two patients with pathologically diagnosed prostate cancers of different prostate volume. IMRT five-field verification plans were produced for each set of patient data and each plan was used for both the 6 MV and 15 MV photon irradiations. Figure 4b shows an example of one such plan. A total of eight phantom measurements were performed, four using the Ge-doped fibres, to accommodate the two cases for the two energies, and an equivalent four for the LiF dosimeters.

2.5.1 Typical Out-of-field doses

Typical in-field and out-of-field dose measurements (the latter meaning dose measurements made outside of the PTV) were carried out using approximately 130 TLD-100 and 500 Ge-doped optical fibres distributed along the length of the RANDO phantom at two specific (x,y) co-ordinates, the location of the x-position changing with the lateral extent of the RANDO phantom. All irradiations were performed using the same Varian Linear Accelerator as

discussed above, doses being delivered at 6MV and 15MV only for the IMRT verification plans. As inferred above, the phantom was positioned on the patient couch of the Varian Linear accelerator (Figure 4c) and irradiations were made using an FSD of 89 cm.

(a)

(b)

(c)

Figure 4. (a) Ten optical fibres were contained in each black plastic rod holder, subsequently inserted into specific holes to replace the tissue-equivalent plugs (b) The IMRT prostate verification plan for the RANDO phantom (consisting of 5 radiation fields) (c) Set-up of the phantom on the Varian Linear Accelerator.

RESULTS AND DISCUSSION

For 6 MV irradiations, Figures 5 and 6 show the average absorbed doses measured by the optical fibres to be in general accord with TLD-100 values, the error bars representing the standard error of the mean reading of the several dosimeters in that position. For both the in-field and out-of-field evaluations no difference is observed between the Ge-doped fibre and TLD-100 measurements; statistical analysis showing differences between the average dose measured using TLD-100 and optical fibres to be insignificant [$p = 0.532$ and 0.206 for the individual IMRT verification plans 1 and 2 respectively].

For 15 MV irradiations, as expected, a large significant difference is to be noted between TLD-100 (both corrected and uncorrected for neutron dose; see below) and optical fibre measurements for both sets of plans for out-of-field measurements, a situation that is not observed for in-field measurements (Figure 7 and 8). The p -value for the out-of-field measurements was found to be significant at < 0.05 . Here it is to be noted that TLD-100 contains 7.5% ^6Li , the thermal neutron absorption cross-section of which is large, $\sim$ a few thousand barn [9,10], influencing the average dose measurements to a considerable extent. The estimates of discrepancies as observed by Kry et al. [5] have been used to offset the present TLD-100 results for the effects of neutron dose, as shown in the two figures. Conversely, the thermal neutron absorption cross-section of the major constituents of the optical fibre, germanium and silica, are both relatively small at ~ 10 barn and ~ 1 barn respectively [10], as also discussed in Ref. [6]. The Ge-doped fibre results have not been corrected for neutron dose.

Figure 5. Average doses obtained for 6 MV irradiations, measured using TLD-100 and Ge-doped optical fibres for Plan 1 for a PTV of 104.1 cm^3 . The TLD-100 and Ge-doped optical fibres response at high doses (from 2300 mGy to 40 mGy) measured up to 10cm from the PTV are shown within the inset figure in figure 5. The inset figure has the same units as the main figure .

Figure 6. Average doses obtained for 6 MV irradiations, measured using TLD-100 and Ge-doped optical fibres for Plan 2 for a PTV of 79.7 cm^3 . The TLD-100 and Ge-doped optical

fibre response at high doses from (1990 mGy to 30 mGy) measured up to 10cm from the PTV are shown as inset in the figure 6. The inset figure has the same units as the main figure .

Figure 7. Average doses obtained for 15 MV irradiations, the graph showing TLD-100 (uncorrected) and TLD-100 (corrected for thermal neutron dose), compared to Ge-doped optical fibre for Plan 1. The TLD-100 and Ge-doped optical fibre response at high doses from (2000 mGy to 20 mGy) are shown as inset in the figure 7 measured up to 10cm from the PTV. The inset figure has the same units as the main figure. The in-field doses being apparent that here the contribution from the neutron dose component to the overall dose is relatively unimportant.

Figure 8. Average doses obtained for 15 MV irradiations, the graph showing TLD-100 (uncorrected) and TLD-100 (corrected for thermal neutron dose), compared to Ge-doped optical fibre for Plan 2. The TLD-100 and Ge-doped optical fibre response at high doses from (1211 mGy to 30 mGy) are shown as inset in the figure 8 measured up to 10cm from the PTV. The inset figure has the same units as the main figure. Again, the in-field doses being apparent that here the contribution from the neutron dose component to the overall dose is relatively unimportant.

CONCLUSION

Ge-doped optical fibres show considerable promise as high spatial resolution dosimeters, being capable of determining typical in and out-of-field doses for 6 MV energy photon beams. The in-dose measurements at 6 MV and 15 MV both show there to be an inappreciable contribution to the overall dose from the thermal neutron component, as expected. Conversely, for out-of-field measurements a highly significant contribution of thermal neutrons to the overall dose is observed. As a result of the finite but relatively small Ge neutron absorption cross-section for photon energies above the photo-neutron production threshold (~ 10 MV), it is clear that the optical fibres do over-respond as a result this photo-neutron component. Further investigations concerning the magnitude of this effect are in progress.

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Figure 1

Figure 2

Figure 3 (left hand graph)

Figure 3 (right hand graph)

Figure 4 (a)

100

Figure 4 (c)

Figure 5

Figure 6

Figure 7

Figure 8