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Wearable glass beads for *in vivo* dosimetry of total skin electron irradiation treatments

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ABSTRACT

Glass beads have recently been proposed for use as radiation therapy dosimeters. Glass beads have a number of characteristics that make them suitable for *in vivo* skin dose measurements, including an ability to be worn on a string, and therefore avoid possible patient discomfort that may result from the use of adhesives. In this study, their use for *in vivo* dose measurements in total skin electron irradiation treatments has been tested. First, the dosimetric properties of cylindrical beads with a 3 mm diameter were characterised using electron fields produced by a linear accelerator. The mean individual bead reproducibility was demonstrated to be within 3%; and a batch variation of 7% was observed. The beads were shown to have a linear dose response, and both dose rate and beam energy independence, within the measurement uncertainty. Phantom measurements were then performed for a total skin electron irradiation beam arrangement, and results compared against optically stimulated luminescent dosimeters at five anatomical sites. For a majority of measurement locations, agreement within 3% was observed between the two dosimetry techniques, demonstrating the feasibility of glass beads as *in vivo* dosimeters for total skin electron irradiation; though further investigation may be needed to minimise uncertainty in results.

1. Introduction

Total skin electron irradiation (TSEI) is a radiation therapy treatment technique that involves the delivery of large radiation fields to the entire body. It is primarily used for the treatment of mycosis fungoides, a form of cutaneous T cell lymphoma. TSEI is a non-conventional modality that involves atypical patient positioning (Karzmark et al., 1987); and therefore it is important to verify the accuracy of delivered absorbed dose to the patient. This can be achieved by performing *in vivo* dosimetry: measurement of dose at various locations on the patient's skin. *In vivo* dosimetry is a well-established and recommended procedure (Kutcher et al., 1994), and a regulatory requirement in the UK. The International Commission on Radiation Units and Measurements Report 24 (ICRU, 1976) states that the accuracy of the delivered absorbed dose to the target should be within ± 5%. This threshold requires accurate dosimetric tools and methodologies that avoid significant and systematic errors.

The most commonly employed detectors for skin dose verifications are radiochromic films (Gamble et al., 2005; Bufacchi et al., 2007) and luminescent dosimeters (Podgorsak et al., 1983; Weaver et al., 1995; Antolak et al., 1998). Luminescent dosimeters measure ionization exposures by the quantification of the intensity of light emitted from the luminescent material when heated (thermoluminescence dosimeters, TLDs) or optically stimulated (optically stimulated dosimeters, OSLDs).

TLDs are frequently used as a patient specific quality assurance (QA) tool for *in vivo* dosimetry (Kutcher et al., 1994; ICRU, 1976), due to their small size and high accuracy. OSLDs have been said to be suitable for *in vivo* dose measurements because of their high accuracy and precision, fast data acquisition, good reproducibility and repeated readouts with a signal decay of only 0.05% (Kutcher et al., 1994), though response is dependent on temperature during both stimulation and irradiation process (Andersen et al., 2008).

The use of glass beads (as commonly used in jewellery) for radiotherapy dose measurements was recently introduced by Jafari et al. (2014a). Glass beads exhibit thermoluminescent properties, and therefore have potential to be used as dosimeters in radiation therapy. The dosimetric properties of glass beads have previously been characterised for 6 MV photon beam; where it was found that they have a linear response over a wide range of dose, and a signal that is

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independent to dose rate, angle of radiation incidence (Jafari et al., 2014a). In this study, a dosimetric characterisation has been performed using a 6 MeV electron beam, to evaluate their possible application as an *in vivo* dosimeter for total skin electron irradiation treatments (TSEI).

Glass beads have desirable physical characteristics for *in vivo* dosimetry, including a small physical size, inert nature and cylindrical shape with a hole in the middle that allows positioning for 2D and 3D arrangements. The cylindrical shape of the beads allow them to be worn by the patient with the aid of a string. This is important, as TSEI treatments are used for patients suffering from skin diseases, where the use of adhesives may result in discomfort.

This work therefore examines how the practicality of using strung glass beads for dose measurements, when compared against taped OSLDs. This is achieved by a characterisation of the dosimetric characteristics of wearable glass beads for electron beams, specifically examining fading, reproducibility, linearity, and dependence on dose rate and beam energy. Their applicability as radiation detectors for *in vivo* dosimetry for patients undergoing TSEI treatment was then tested by phantom measurements under treatment conditions.

2. Methods and materials

2.1. Preparation of glass beads

The dosimetric properties of commercially available wearable glass beads manufactured by Mill Hill (Japan) were studied to investigate their suitability as dosimeters in TSEI treatments. These glass beads were available in various shapes and sizes, however in the present work, 3 mm sized cylindrical 'icy white' beads were studied.

Wearable glass beads are usually coated and painted with reflective metallic elements making them appealing for jewellery purposes but not suitable for dosimetry measurements. In regards to thermoluminescent measurements, the coatings and paint (Fig. 1) may prevent the readout system from correctly reporting luminescence efficiency, and therefore it was necessary to remove all the coatings and paintings before using them as dosimeters. Glass beads were cleaned with a nitic acid solution (with a concentration of approximately 20%) in an ultrasonic bath for 30 min.

Before exposing glass beads to radiation within the clinic, annealing was performed in order to clear any existing irradiation history. Annealing conditions were taken from Jafari et al. (2014a). Aluminium foil was used to wrap the beads prior to placement in an annealing oven. The glass beads were heated at 400 °C for 1 h with a ramp rate of 16 °C per minute, then cooled at a rate of 1 °C per minute and were subsequently kept at 80 °C for a total of 18 h. This annealing step reduced the residual signal to less than 0.3%. The glass beads were wrapped in an opaque bag and stored in darkness to minimise light exposure for at least 18 h for stabilisation purposes.

Fig. 1. Cleaned glass beads from Mill Hill (Japan).

During annealing, the glass beads were arranged on aluminium wire, with coloured beads placed after every 10 beads in order to keep track of the sequence.

2.2. Glass bead processing

The irradiation of the glass beads was performed at the Royal Brisbane & Women's Hospital using a Varian 21iX accelerator (Varian Medical Systems, Palo Alto, USA). Characterisation irradiations were performed under local reference conditions, using a 6 MeV electron beam, with a 10×10 cm^2 field size and a source-to-surface distance of 100 cm. These measurements were performed in a 30×30 cm^2 water equivalent phantom (virtual water) at depth of maximum dose, D_{max}, of 1.3 cm. Glass beads were placed on top of 0.7 cm of water-equivalent jelly bolus material, to minimise air gaps, with 7 cm of virtual water backscatter material. Irradiations were performed with the beads threaded onto an aluminium wire, placed in the centre of the radiation field, to ensure that all beads received the same dose.

A TL 3500 Harshaw reader was employed to study the radiation response and TL yield of the glass beads. The readout cycle involved a planchet preheating temperature of 160 °C, to clear any unstable peaks, followed by a readout temperature of 300 °C using a heating rate of 35 °C/s to collect the thermoluminescence yield from dosimetric peaks. For each measurement described below, the readings were performed approximately 10 h after exposure for stabilisation purposes, unless otherwise specified. The annealing cycle described in Section 2.1 was performed after each irradiation and readout.

2.3. Response characterisation

To characterise the radiation response, or sensitivity, of each individual bead, a dose of 200 cGy was delivered at a dose rate of 400 MU/min under reference conditions. A sensitivity correction, a ratio of the mean signal of the batch to the individual bead signal, was calculated and applied to each subsequent readout. This approach replicates the element correction factor employed when using OSLDs (Dunn et al., 2013). The variation in sensitivity across the batch was also measured.

Reproducibility was tested using 18 glass beads, by performing 3 consecutive linear accelerator irradiations of 200 cGy delivered at a dose rate of 400 MU/min.

To investigate the linearity of the response of the glass beads to absorbed dose, 11 discrete doses in the range 1–1500 cGy were delivered to a batch of 33 glass beads (3 glass beads per dose) at a dose rate of 400 MU/min. Readings were corrected for individual bead sensitivity.

The dose rate dependence of the glass beads was investigated by delivering a constant dose of 200 cGy using standard dose rates of from 100, 200, 300 and 400 MU/min, in addition to the high dose rate ($HDRe^-$) mode used in TSEI treatments (approximately 2000 MU/min). Due to the difference in calibration conditions for the high dose rate mode, the machine output was verified using a PTW Advanced Markus ionization chamber (PTW, Freiburg, Germany). 3 glass beads were irradiated at each dose rate. Readings were corrected for individual bead sensitivity.

To characterise energy dependence, the dosimeters were irradiated with nominal electron beam energies of 6, 12 and 18 MeV. The delivered dose was 200 cGy at a dose rate of 400 MU/min under reference conditions, with the glass beads placed at the appropriate depth of maximum dose for each electron energy used. Measurements were performed using 6 beads for each beam energy. Readings were corrected for individual bead sensitivity.

The signal fading rate of the glass beads was examined using a single glass bead, using doses of 200 cGy. The fading rate was tested for

various periods between irradiation time and readout time, from 15 mins to 24 h. Readings were corrected for individual bead sensitivity.

The uncertainty in bead measurements for an arbitrary dose was determined using the following equation:

$$\sigma_{total}=\sqrt{\sigma_{lin}^2+\sigma_{repro}^2+\sigma_{dr}^2+\sigma_{lig}^2+\sigma_{ro}^2}$$

where σ_{lin} is the uncertainty in linearity response, σ_{repro} is the uncertainty in reproducibility, σ_{dr} is the uncertainty in dose rate response, σ_{lig} is the uncertainty in reference light from the TL reader, and σ_{ro} is the uncertainty in readout time.

2.4. Phantom treatment

Phantom measurements were performed under TSEI treatment conditions using a RANDO phantom (Radiology Support Devices, Long Beach, USA) placed at a source-to-surface distance of 390 cm. A 6 MeV high dose rate beam was used to deliver a total of 2400 monitor units. To maximise dose uniformity across the phantom, a dual-field arrangement was used, with linear accelerator gantry angles of 72.3° and 107.7°. The beam was modified with the addition of scattering energy degrader screen, used clinically to improve dose uniformity at the treatment depth. The scattering screen was placed 40 cm in front of an anthropomorphic RANDO phantom (350 cm source-to-surface distance). This beam arrangement approximates the delivery of dose to a single patient position treated using the Stanford technique (Karzmark et al., 1987).

InLight nanoDot OSLDs (Landauer Inc. Glenwood, USA) and glass beads were used to measure absorbed dose at five phantom locations, shown in Fig. 2. The glass bead dosimeters were strung on the phantom, while OSLDs were taped in the same locations (representing current clinical practice). Dose measurement points 1–3 were anteriorly located, and expected to measure similar doses (due to dose uniformity across the patient). Dose measurement points 4 and 5 were laterally located, and therefore more susceptible to dose variations due to dosimeter positioning, scatter conditions and angular dependence of the dosimeter. For each measurement location, 2 glass beads and 2 OSLDs were irradiated.

The OSLDs used in the study were previously calibrated for clinical use (for TSEI treatments) using a 12 MeV beam. OSLDs were scanned using an InLight MicroStar reader (Landauer Inc. Glenwood, USA), with readings made 2 h after irradiation.

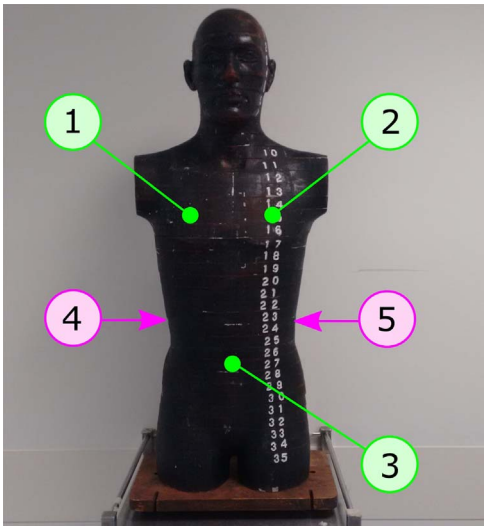

Fig. 2. Anthropomorphic phantom showing the five anatomical positions used for dose measurement in TSEI treatment.

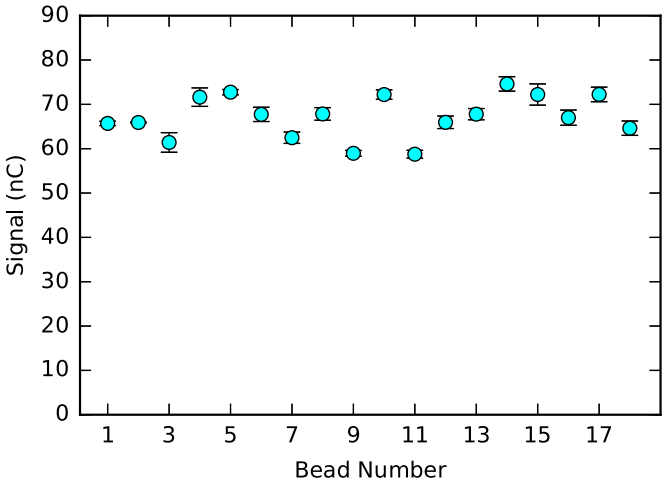

Fig. 3. Repeated TL signal reading against glass bead number.

3. Results and discussion

3.1. Response characterisation

The radiation response varied between 55 and 70 nC across the cohort of beads. The variation coefficient across the batch was found to be ± 7%, obtained from the average of the standard deviation of unscreened glass beads. This was larger than the batch variation of ± 7.4% (2 standard deviations) reported for a batch of screened beads by Jafari et al. (2014a). The variation is similar to the range of element correction factors of ± 6% for a sample of 11 OSLDs reported by Asena et al. (2014). The batch variation observed here is smaller than reported for some other forms of thermoluminescent dosimeters, including LiF:Mg,Cu,Si, reported to be approximately 10% (Kim et al., 2008).

Given the large difference in reported variations for this unscreened batch and the mass-screened batch investigated by Jafari et al. (2014a), it is probable that the variation may be a result of differences in mass, volume, composition and/or physical conductivity.

Signal reproducibility, or variation in response for individual beads, is presented in Fig. 3. The mean reproducibility of the glass bead (*i.e.* the standard deviation in signal response) was found to be within 3%. Kirby et al. (1992) reported standard deviations of 2.3% for LiF TLDs for electron beams. Jursinic (2007) reported reproducibilities of 1.5% for TLDs and less than 1% for OSLDs, for photon beams.

The sensitivity-corrected response of glass beads with varying dose is presented in Fig. 4. The dose response was found to be linear, within measurement uncertainty, and with an R^2 correlation coefficient of 0.9989. This correlation is similar to the R^2 coefficient of 0.9989 reported by Jafari et al. (2014a).

The glass beads were demonstrated to be dose rate independent, within ± 3%, for the dose rates tested. The dose rate responses are presented in Fig. 5. This result confirms the dose rate independence previously reported by Jafari et al. (2014a).

Energy independence was also demonstrated for the electron energies tested, within measurement uncertainties. These results are presented in Table 1, and confirm the energy independence previously reported by Jafari et al. (2014b). This behaviour compares favourably with reported LiF powder and glass rod dosimeters energy dependences of 4.8% (Rah et al., 2008).

Fig. 6 presents the fading rate of a single glass bead. The rate of fading was found to be 12% within 24 h after irradiation, whereas the signal decay observed when the readouts are done within the first 40 mins after irradiation was within ± 0.9%. It is suggested that readouts are performed after 10 h with fading corrections performed as necessary.

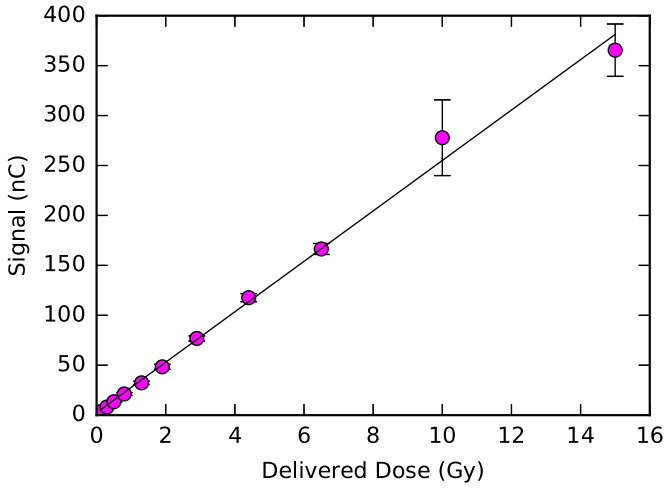

Fig. 4. Response of glass bead dosimeters to varying doses.

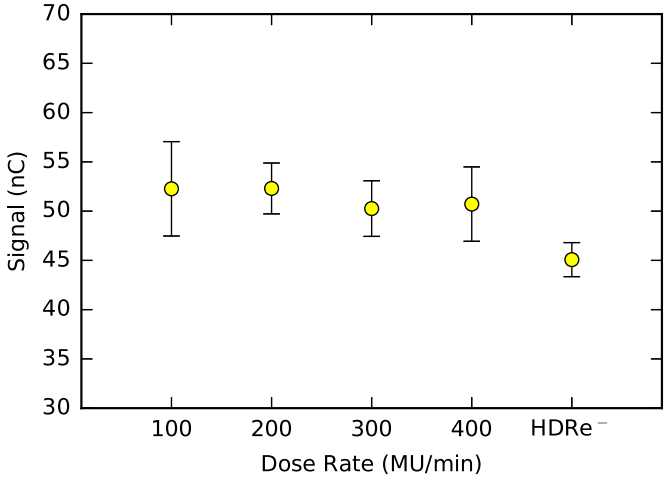

Fig. 5. Response of glass bead dosimeters to varying dose rates, including the high dose rate electron mode (HDRe⁻).

Table 1
Energy dependence across 6, 12 and 18 MeV beams.

Energy (MeV)	Average signal (nC)	Standard Deviation (nC)	Uncertainty (nC)
6	68.5	3.3	3.9
12	68.1	2.0	2.8
18	69.2	1.8	2.8

The combined uncertainty of the glass bead measurements was found to be 5.7%. The individual sources of uncertainty are presented in Table 2. AAPM Report No 23 suggests that a 5% accuracy can be obtained with careful TLD dosimetry procedures (Karzmark et al., 1987).

The linearity, dose rate and reproducibility uncertainties presented in Table 2 have been adjusted to allow an individual account of delivery uncertainties, specifically linear accelerator output, beam flatness (uniformity of dose over the beads) and measurement setup.

3.2. Phantom treatment

OSLD and glass bead dose measurements are presented in Table 3. Measurements agreed within bead measurement uncertainty for dose at positions 1–3, and disagreed at positions 4 and 5.

In positions 1–3, the dose measured by the glass bead dosimeters

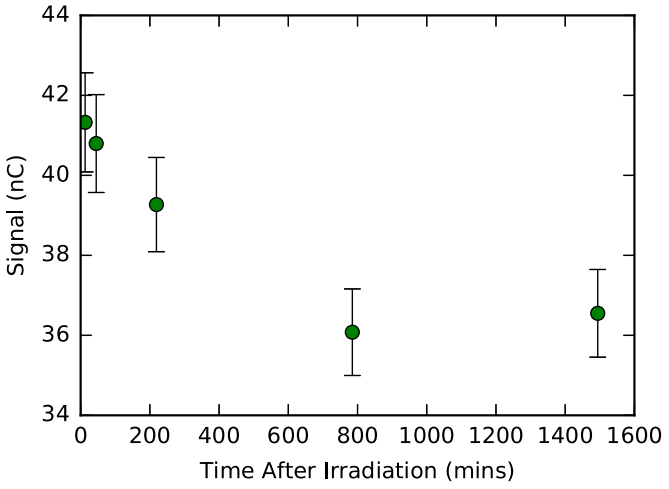

Fig. 6. Response of a glass bead dosimeter for varying post-irradiation readout times.

Table 2
Relative standard uncertainties derived from TLD measurements results.

Source of uncertainty	Standard uncertainty (%)
Linearity	4.0
Dose rate	2.5
Reproducibility	2.5
Accelerator output	0.3
Beam flatness	0.7
Measurement setup	1.5
Read out period	0.9
TLD readout process (Ref light)	0.005
Total uncertainty	5.7%

Table 3
Absorbed dose measured at five anatomical sites using glass beads *vs* OSLDs.

Position	OSLD dose (cGy)	Bead dose (cGy)	Difference
1	141	145	2%
2	146	142	3%
3	143	147	3%
4	54	90	67%
5	59	63	7%

varied from the OSLD dose by 2–3%, a smaller variation than measurement uncertainty. These positions correspond to the measurement locations used in the determination of monitor units (or beam time) for TSEI treatments, so this agreement suggests that the replacement of OSLDs with glass beads would not result in a change in clinical practice. The dose across these 3 positions is approximately equal, which was expected for this dual field beam arrangement.

The disagreement between glass beads and OSLDs exceeds measurement uncertainty in positions 4 and 5. There are a number of possible causes for this increased disagreement. The dose measurements in these locations are more susceptible to variations resulting from deviations in setup, due to the oblique incidence of the field and irregular phantom contour. Additionally, any angular dependence effects would be observable. Jafari et al. (2014a) reported that glass beads exhibited angular independence in photon beams, though this may not hold true for electron beams. OSLDs have been reported to exhibit angular dependence of the order of 7% for a 90° rotation in orientation for a photon beam (Lehmann, 2014).

4. Conclusion

This study examined the dosimetric properties of wearable glass beads in electron beams. The wearable glass beads demonstrated a

linear dose response, and were observed to have dose rate and energy independence.

There was, however, a large uncertainty in the dose measurements performed, due in part to variations in sensitivity for single beads. The large batch variation observed in this study highlights the value of a screening process, such as the mass screening performed by Jafari et al. (2014a).

Measurements performed under TSEI treatment conditions demonstrated the feasibility of glass beads as *in vivo* dosimeters, with variations of less than 3% between glass bead and OSLD measurements for the 3 anterior measurement locations.

The glass bead dosimeters have the potential to measure absorbed dose without being taped directly on the patient's skin, and therefore have the potential to minimise patient discomfort while ensuring accurate dose delivery.

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