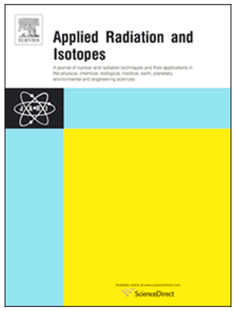

Microscope cover-slip glass for TLD applications

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Microscope Cover-slip Glass for TLD Applications

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Abstract:
As a result of the various evolving needs, thermoluminescence dosimetry is constantly under development, with applications intended in environmental and personal radiation monitoring through to the sensing of radiotherapy and radiation processing doses. In radiotherapy dosimetry challenges include small-field profile evaluation, encompassing the fine beams of radiosurgery, evaluations confronting the steep dose gradients of electronic brachytherapy and the high dose rates of FLASH radiotherapy. Current work concerns the thermoluminescent dosimetric properties of commercial low-cost borosilicate glass in the form of thin (sub-mm to a few mm) plates, use being made of microscope cover-slips irradiated using clinical external-beam radiotherapy facilities as well as through use of ^{60}Co gamma irradiators. In using megavoltage photons and MeV electrons, characterization of the dosimetric response has been made for cover-slips of thicknesses up to 4 mm. Reproducibility to within +/5% has been obtained. In particular, for doses up to 10 Gy, the borosilicate cover-slips have been demonstrated to have considerable potential for use in high spatial resolution radiotherapy dosimetry, down to 0.13 mm in present work, with a coefficient of determination in respect of linearity of > 0.99 for the thinner cover-slips. Results are also presented for 0.13- and 1.00-mm thick cover slips irradiated to ^{60}Co gamma-ray doses, initially in the range 5- to 25 Gy, subsequently extended to 5 kGy to 25 kGy, again providing linear response.

Keywords: borosilicate glass; thermoluminescence, dosimetry, radiotherapy

Introduction:

The research addressed herein concerns a highly effective yet economic means of dosimetry, applied to the sorts of doses delivered in fractionated external-beam radiotherapy, through to radiation sterilization and lower dose radiation processing. Microscope cover-slip glass (a borosilicate medium) forms the focal interest, offering favourable characteristics for thermoluminescence dosimetry (TLD). In the initiating work of Amal Alqhatani et al. (2020) reproducibility to within +/5% was reported, the glass also being shown to be linearly responsive to dose, yielding a coefficient of determination of > 0.99 for doses up to the investigated level of 10 Gy, according with the desire for TLD detectors to have a linear absorbed dose response (McKeever 1985). Potential advantages of the glass include the fact that the particular medium can withstand high temperatures but also that it softens at ~ 700□C, sufficiently low to provide practical scope for fabrication into various shapes. Being glass, it can also be used in aqueous environments. The TL behaviour arises from the mix of elements in the insulating medium (boron included), producing a rich level of defects, making it of high utility.

The rich level of defects in a high-temperature insulating medium is exactly what is needed in providing for a sensitive means of TLD. Widely available in commercial quantities and importantly for present circumstance produced as uniform flat plates of mm to sub-mm thickness, the TL sensitivity of these products renders them of particular interest for radiotherapy and sterilization applications. In particular, one has in mind the high spatial resolution needed in order to define the so-called build-up region (Somoyot Srisatit et al., 2013), also in small field profile evaluations including the very fine beams of radiosurgery, the steep dose gradients of electronic brachytherapy, the high dose rates of FLASH radiotherapy and kGy doses of radiation sterilization.

In prior investigations, at doses from sub-Gy through to excess of 10 Gy (using 120 kVp x-rays, ^{60}Co-gamma-rays and linac-based x- and electron beam irradiations), Amal Alqhatani et al. (2020) showed borosilicate glass of nominal thickness 1.0 to 1.2 mm to offer an effective means of dosimetry. This has subsequently prompted the question as to whether in use of such a dosimetric medium a thickness dependency might prevail. Accordingly, herein, in an initial set of investigations that have covered a similar range of doses as before, investigations have been made using several cover-slip glass thicknesses (1.2 mm, 3 mm and 4 mm), providing for a more comprehensive set of TL yield measurements for linacbased x- and electron beam irradiations. The data have all been obtained at the nominal sub-surface point of maximum dose build-up, the latter from the very beginning prompting the development of clinical MV accelerators to provide the benefit of the well-known skin-sparing effect in addition to penetration. The nominal photon energy of 6 MV is a popular choice in deep tumour radiotherapy treatments for adults of average size while 6 MeV electron therapy is a favourable choice for superficial tumour treatments. In use of the several thicknesses of microscope cover-slip glass, differences in TL yield have been anticipated, arising as a result of the initial build-up towards electronic equilibrium with predominance of attenuation beyond. Other influences, bremsstrahlung production within the glass-based dosimeter included, are expected to be very much smaller factors. In a subsequent set of investigations, using ^{60}Co irradiators, the dose range was extended to cover the radiation sterilization and lower-end dose radiation processing regimes, use now being made of thinner cover-slips.

2.0. Materials and Methods *2.1. Borosilicate glass slides*

Following on from the first dosimetric study of commercial microscope cover-slips samples (Amal Alqhatani et al., 2020), the initial series of investigations made use of cover-slip samples of 1.2-, 3- and 4 mm thickness (supplied by GSC International Inc), density 2.23 g cm^{-3}, prepared in regular squares of approximate size 4 x 4 mm^2 to allow subsequent placement in the heating planchette of the TL reader. Specific use was made of unfrosted clear glass portions, noting in serving their intended function that cover-slips are necessarily of high optical quality, hence of high transparency, physical uniformity and homogeneity. The second series of measurements, made at more elevated doses but again utilizing commercial B_2O_3 glass slides (supplied by HmbG Chemicals, Germany), this time made use of samples of thickness 1.0 ± 0.01 mm and 0.13 ± 0.02 mm, cut into regular pieces of approximate size 5 x 5 mm^2. Three sets of samples were prepared for each measurement. All samples were annealed at 400 °C for an hour to remove any prior luminescence arising from handling (strain, oxidation etc) and background radiation, a measure intended to standardize their thermal history. Prior to irradiation the samples were then kept at room temperature in the annealing pot, lined and covered with aluminum foil to minimize the effect of light exposure.

The hospital based linac irradiations were carried out at the Royal Surrey County Hospital NHS Foundation Trust use being made of a Varian Truebeam linear accelerator. For the 6 MV irradiations, and a 10 × 10 cm^2 field, the cover-slip samples were located on the central-axis of the field at the point of maximum build-up of 1.5 cm below the full-scatter phantom surface (the position of electronic equilibrium), use being made of a 20 × 20 × 20 cm cube of the proprietary medium *solid-water*™. Equivalently, for the 6 MeV irradiations, again with a 10 × 10 cm^2 field, the cover-slip samples were located on the central-axis of the field at again 1.5 cm below the phantom surface. The source-to-surface distance (SSD) was set at 100 cm in both cases. In evaluations at the University of Surrey use was made of a Riso TL/OSL reader (model TL/OSL-DA-20), as detailed in Amal Alqhatani et al. (2020), comprising a light detection system (a photomultiplier tube (PMT) in combination with suitable detection filters), a luminescence stimulation system (thermal and optical) and an irradiation source for calibration purposes. The complete details of the system are available at file:///Users/davidbradley/Downloads/Risoe-Readerand-Beta-Counter-Product-catalogue-1803a.pdf

The measurements were all carried out in a vacuum chamber (lowest pressure < 2 × 10^{-2} mbar). A readout temperature of 370 °C for 34.5 seconds was selected, informed by studies at Surrey for silica glass (Ley et al, 2019), with use of a heating rate cycle of 10 °C s^{-1} and holding time of 20 seconds, making a total readout time for each sample of 54.5 seconds. TL yields per unit mass are quoted in the results herein.

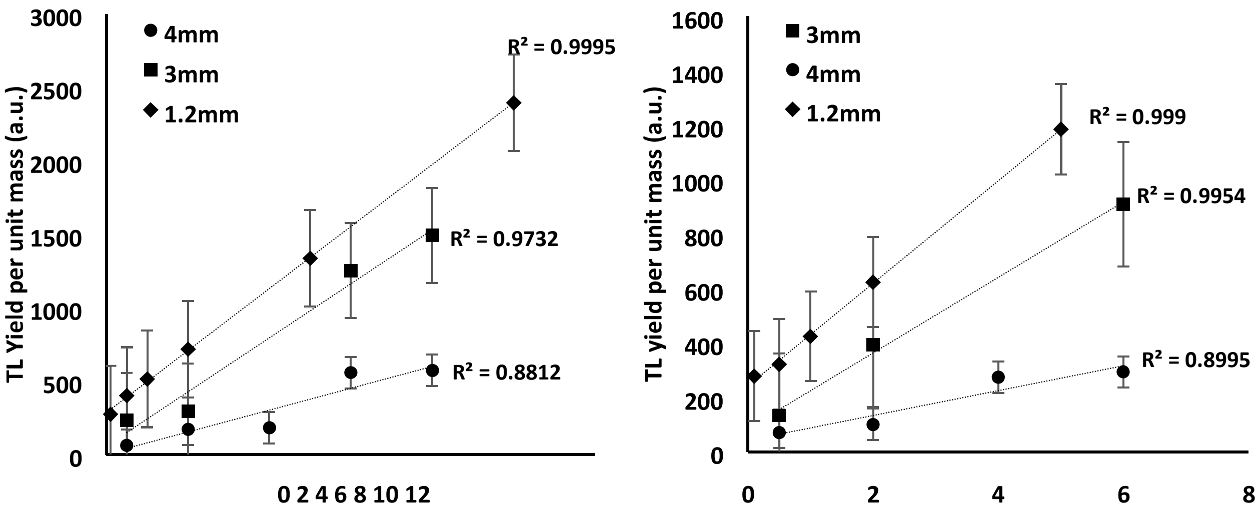
For the 0.13- and 1.0 mm cover-slips, TL irradiations were conducted for doses from 5 to 25 Gy, using a Gammacell 220 ^{60}Co facility, delivering a dose rate of 1.61 Gy min^{-1} at the time of irradiation, located at the Department of Physics, University of Malaya (UM), while for 5 kGy to 25 kGy dose irradiations these were conducted at the *SINAGAMA* (literally 'gamma-ray') irradiation facility at the Malaysian Nuclear Agency, delivering a dose rate of some 10 Gy min^{-1} at the time of irradiation. For all investigations carried out in Malaysia, the cover-slips were readout using a Harshaw 3500 TLD reader, located in the University of Malaya (UM) Department of Physics. Continuing UM practice for glass dosimeters, use was made of preheat temperature, acquisition maximum temperature and anneal temperature of 50 °C, 300 °C and 350°C, respectively and an acquisition temperature ramp rate of 25 °C/s. In both Surrey and UM a nitrogen gas supply was connected to the reader.

Results and Discussion:

3.1. Dose response for the different thickness coverslips

In Fig. 1(a), for doses from 0.5 Gy to 8 Gy, the mass-normalized TL yields are shown for the 1.2-, 3- and 4 mm thick coverslips, obtained from use of the Truebeam clinical linear accelerator operated at an accelerating potential of 6 MV. For the 1.2 mm thick cover-slip in particular, the photon response accords with the desire for TLD detectors to have a linear response to absorbed dose (McKeever 1985). The TL yield per unit mass is an inverse function of cover-slip thickness, being greatest for the 1.2 mm sample with a coefficient of determination R^2 of 0.999 compared to an R^2 of 0.973 and 0.881 for the 3 mm and 4 mm thick cover-slips respectively. The reduction in TL response for cover-slip thicknesses greater than 1.2 mm is interpreted to arise from the associated increasingly greater sampling of the region of build-up to the electronic equilibrium dose-maximum and attenuation beyond compared to that for the 1.2 mm, also implicit in the results of Scarboro et al. (2011) and Reynolds and Higgins (2015). Figure 1(b) shows the equivalent responses arising from 6 MeV electron beam irradiations, again showing similarity of pattern. One further observation is the greater response of the photon-irradiated cover-slips, a potential result of the polyenergetic spread of the photons and with it an enhanced photoelectric dependence from the dominant silaceous medium of the cover-slips (with silicon having an atomic number of 14 and oxygen with an atomic number of 8).

Results for the 0.13- and 1.00-mm thick cover slips, irradiated to ^{60}Co gamma-ray doses in the range 5- to 25 Gy and from 5 kGy to 25 kGy (the latter applicable in radiation sterilization through to radiation processing) are shown in Figs. 2(a) and (b) respectively. These concern direct irradiations in the absence of any intervening or underlying scatter medium. The mean and standard deviations are shown for each dose. As opposed to the situation observed in Fig 1, the 1.0 mm cover-slip demonstrates very much greater TL yield than for that obtained in use of a thinner (0.13 mm) cover-slip, a matter prevailing for both gamma irradiation dose regimes. Further apparent is that the gradient is very much greater for the 1.0 mm thick cover slip compared to that for the 0.13 mm cover slip, again obverse to that seen for the medical linac irradiations. Here it is posited that during irradiation, with a much greater propensity for temperature rise in the thinner sample, this leads to a greater degree of self-annealing of occupied defects, reflected in the associated lower TL yield per unit mass.



(a) Dose (Gy)

(b) Dose (Gy)

Figure 1 Dose response for 3- and 4 mm glass slides when irradiated to photons generated at (a) 6 MV and (b) 6 MeV with dose ranging from 0.5 to 8 Gy.

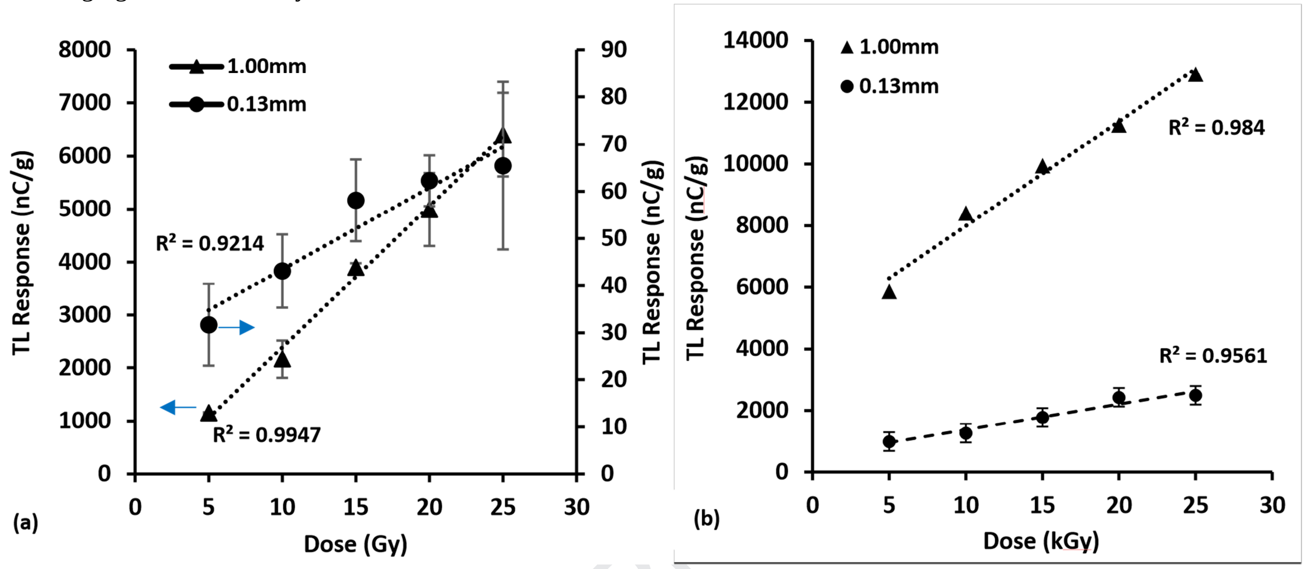


Figure 2 Dose response for 0.13 mm and 1.0 mm glass slides when irradiated to ^{60}Co gamma-rays for doses in the range: (a) 5 – 25 Gy (Note: The right-hand side y-axis represents the data for 0.13 mm glass slide) and; (b) 5 kGy – 25 kGy.

3.2. Glow curves for the different thickness coverslips

The glow curve, representative of the population of trapped electrons, is shown in Figure 3 for the 3 and 4 mm cover slips, respectively while Figure 4 shows the respective glow curve for 0.13 mm and 1.00 mm cover slips. For the series of glow curves arising from linac irradiations, which for the sake of clarity are shown only for the 2 Gy and 8 Gy doses, a disproportionate growth in TL yield with dose is apparent, most noticeably for the photon irradiations, being less for the thicker than for the thinner cover-slips. Fig. 1 does indeed show associated evidence of non-linearity for the thicker samples, the value of R^2 reducing with increase in thickness. A further observation to be had from comparing the photon and electron irradiation glow curves is the noticeable albeit marginal narrowing of the glow curve distribution for the latter, a potential effect of the quasi-monoergetic character of the electron irradiations compared to the polyenergetic photon spectrum.

In regard to the gamma-ray irradiations, the 1.0 mm thick cover-slips show clear evidence of the accessing of traps of similar depth to those in the case of the linac-irradiated cover-slips, peaking within the range 200 to 220 °C, both for the 5 Gy as well as the 20 Gy irradiations. Conversely, for the 0.13 mm thick cover-slips, the recorded glow curves peak at markedly lower temperature, at some 150 to 175 ºC. The more broad single-peaked structure of Fig. 4, covering temperatures in the range 50 °C to 350 °C, with a further apparent shift towards lower temperatures for the 0.13 mm cover-slips hints at preferential selfannealing of the deeper traps.

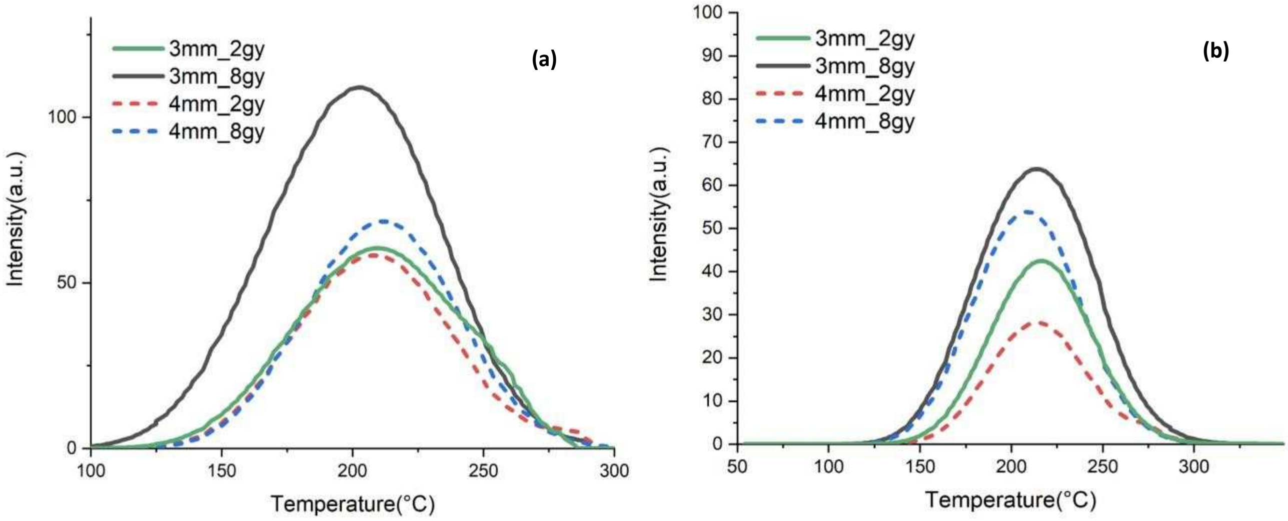


Figure 3 Glow curves for 3- and 4 mm glass slides when irradiated to photons generated at (a) 6 MV and; (b) 6 MeV.

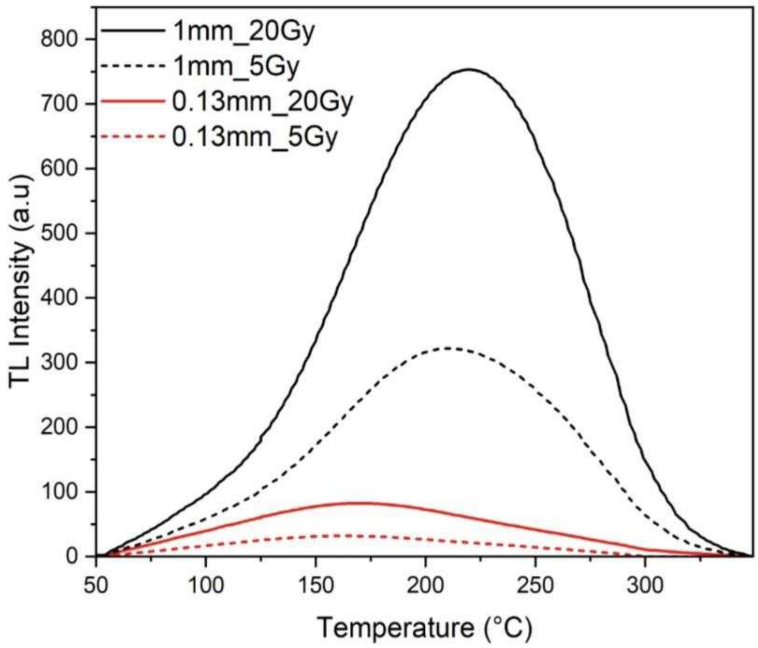


Figure 4 Glow curves for 0.13 mm and 1.00 mm cover-slips, extracted from measured data using ^{60}Co irradiations.

The energy dependence of two thicknesses of cover-slip (0.13- and 3 mm) have also been investigated at the University of Malaya, irradiated using an ERESCO 200 MF4 X-ray beam facility operated at accelerating potentials providing a range of nominal energies, 20 to 80 keV. In all cases the cover-slips were exposed to an absolute dose of 5 Gy. The graph of TL yield versus energy (in keV) is presented in Fig. 5. Each data point represents the mean of three individual glass slide readings, normalised by mass.

Over the range of photon energy, the dominant interaction is the photoelectric effect, allowing correction factors to be obtained through calibration.

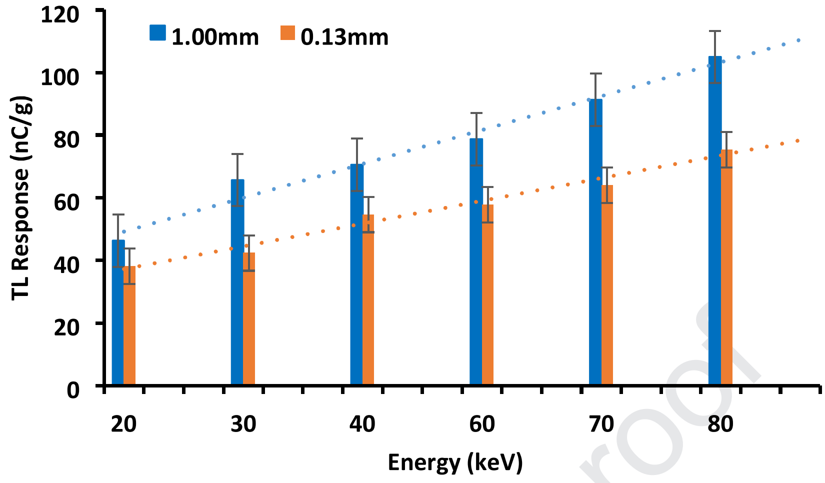
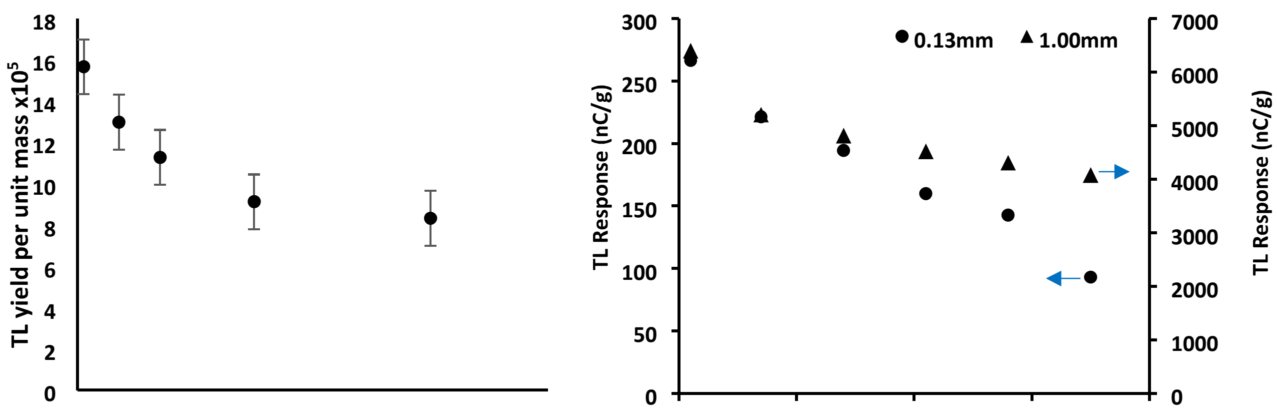


Figure 5 The energy response of 0.13 mm and 1.00 mm glass slides subjected to x-ray exposures of 5 Gy.

3.3 Fading

Post-irradiation TL signal loss, conventionally referred to as fading, has been studied for the more and least responsive cover-slips, varying the time between irradiation and readout, with storage at room temperature under darkened conditions prior to readout. The 1.2 mm thick cover-slips were irradiated to a 2 Gy dose of 6 MV photons and sub-grouped into five groups, corresponding to storage of 1 day, 1 week, 2 week, 1 month and 2 month periods) (Fig 6(a)). The fading rate was found to be 50% following the first 60 days of storage, promising when compared to the 28 day fading rates of 25-60% for commercially available LiF and $CaSO_4$ based TLDs (Harvey et al., 2010). For the 0.13- and 1 mm coverslips, these were exposed to ^{60}Co gamma rays, delivering a dose of 25 Gy. The graphs of TL yield (in counts per second per unit mass of glass) against storage time (in days) have been plotted, as shown in Fig. 6(b). For the 0.13 mm glass slides, the loss in TL yield was found to be 64% over 35 days post irradiation while for the 1.00 mm glass slides, over the same period of study, a lower loss in TL yield was found, at some 36% of the original value. This ties in with the corresponding glow curves, with a higher probability of transition for the lower activation energies of the 0.13 mm cover-slips.



0 20 40 60 80 0 10 20 30 40 (a) Days (b) Days

Figure 6 Graph of residual TL signal against annealing time for: (a) 1.2 mm cover slips; (b) 0.13 mm and 1.00 mm coverslips, investigated for a 35 day period post gamma-ray irradiation to a dose of 25 Gy. (Note: The right-hand side y-axis of Fig. 1(b) represents the data for the 1.00 mm thick glass slide.

3.4. Dose rate setting dependence

Using a fixed dose of 2 Gy delivered by the 6 MV photon source, investigation has been made of the response of the 1.20 mm thick cover-slips for dose rates in the range 100-600 cGy/min. Note is made that a conventional external beam linear accelerator radiotherapy dose-rate would be 400 cGy/min. The results, displayed in Fig. 7, indicates that although least-square fit points to a very weak trend towards increased yield with dose-rate, within uncertainties there is effective dose rate independence, a matter also shown by Jafari et al. (2014) for silica-glass beads.

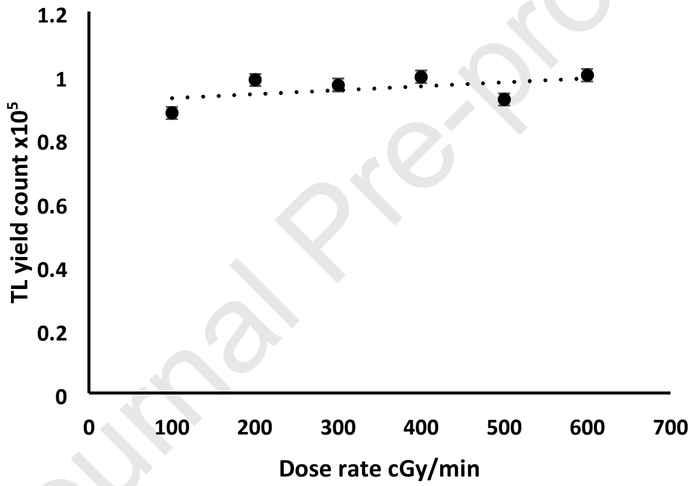
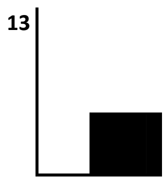


Figure 7 TL response of glass slides (1.2 mm) irradiated with the same dose delivered at different dose rates of 100 - 600 cGy/min, using 6 MV photons (normalised to that at 600Mu/min).

3.5. Angular dependence

The angular dependence of dosimeters was investigated by positioning the 1.20 mm slides on a water phantom at angles of 90°, 60°, 45° and 0° from the cover-slip axis. A radiation dose of 4 Gy was given using 6 MV photons and a 10 × 10 cm^2 field. The response of the borosilicate glass slides to different angles of irradiation using photon beams was found to be within 1% and thus independent of beam angle (Fig. 8), advantageous compared to other choices of dosimeter of small size, including diodes and diamond detectors (Araki et al., 2003, 2004).



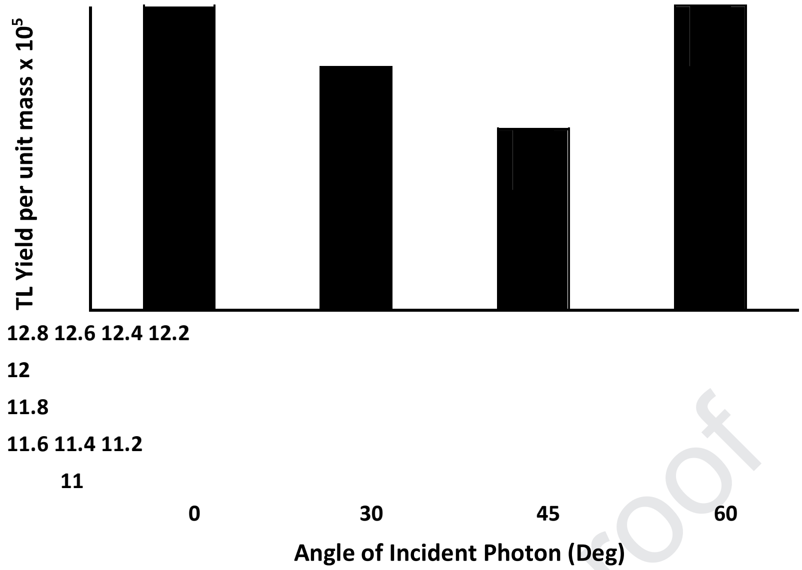


Figure 8 Response of cover-slips when irradiated at 0°, 30°, 45° and 60°, using photons

Conclusions

Using 6 MV, 6 MeV and ^{60}Co gamma irradiation, workable TL yields and performance have been demonstrated for several thicknesses of borosilicate microscope glass. Of these thicknesses, that of the

1.20 mm cover-slip has provided the best response, the latter providing linearity against dose for doses in the range 5 to 25 Gy and from 5 kGy to 25 kGy. The 1.20 mm glass slides also suffer lesser fading, at ~36% of the original TL yield 35 days post irradiation compared to the 0.13 mm glass slides at > 50%. The 1.00 mm glass slides offer considerable potential for both low and high range dosimetry applications, in particular in radiotherapy and radiation sterilization/processing, respectively. A point not explored herein, but nevertheless worth mentioning is that the boron content, at a concentration of some 4% (weight %), points to potential use in neutron dose evaluation, of importance in seeking accurate radiotherapy dosimetry at elevated energies, notably at >10 MV nominal photon energy and >10 MeV for electrons.

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Highlights

- TL yield of borosilicate microscope cover-slips investigated.
- Cover-slips, 1.2 mm thick and below, linear for linac radiotherapy dose regimes and for ^{60}Co irradiations up to 25 kGy.
- Origin of the underpinning defects analysed via glow curve study.
- For 1.00 mm glass slides 35 days post-irradiation, TL fading found to be some 36% of the original value.

10 March 2020

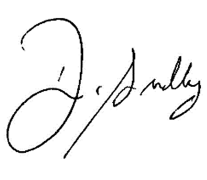
Dear Editor:

Manuscript Title: **Microscope Cover-slip Glass for TLD Applications**

Please find attached a revised copy of the manuscript as entitled above, together with response to referee comments. We look forward to hearing from you in due course.

Yours sincerely,

Amal Alqhatani



Statement of Conflicts of Interest

There are no conflict of interest.