

Response of Nanodot Optically Stimulated Luminescence Dosimeters to Therapeutic Electron Beams

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Abstract

Response of $\text{Al}_2\text{O}_3:\text{C}$ -based nanoDot optically stimulated luminescence (OSL) dosimeter was studied for the dosimetry of 6, 9, 12, 16, and 20 MeV therapeutic electron beams. With reference to ionization chamber, no change in the response was observed with the change in the energy of electron beams for the field size from $6\text{ cm} \times 6\text{ cm}$ to $25\text{ cm} \times 25\text{ cm}$, dose rates from 100 MU/min to 600 MU/min, and the linearity in the response up to 300 cGy. The fading of the transient signal was higher for 20 MeV electron beam than that of 6 MeV electron beam by about 5% as compared to value at 20 min after irradiation. The depletion of OSL signal per readout in 200 successive readouts was also found to change with dose and energy of electron beam from 6 MeV (9% and 12% per readout at 2 and 10 Gy, respectively) to 20 MeV (9% and 16% at 2 and 10 Gy, respectively). The OSL sensitivity changed in the range from 2% to 6% with accumulated doses from 2 to 8 Gy and with electron energy from 6 to 20 MeV, but the sensitivity could be reset using an optical annealing treatment. Although negligible fading for postirradiation storage from 20 min to several months, acceptable precision and linearity in the desired range, and high reproducibility makes nanoDot dosimeters very attractive for the dosimetry of therapeutic electron beams, a note should be made for changes in sensitivity at doses beyond 2 Gy and electron beams energy dependence in reuse, short-term fading, and signal depletion on repeated readout.

Keywords: Dosimetric characteristics, electron beam, nanoDot dosimeter, radiotherapy

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INTRODUCTION

Megavoltage electron beam therapy is an important treatment modality in radiotherapy, providing unique choice to treat superficial tumors.^[1,2] Electron beams have been produced initially by betatrons, and by microtrons followed by linear accelerators.^[3] An appropriate dosimeter must be used to determine the dose accurately at a point with minimum perturbation of electron fluence.^[4] The drawbacks of the dosimeters such as destructive technique, annealing process^[5,6] and ineffectualness in reestimating the dose with thermoluminescent dosimeters, reduced lifetime with metal oxide semiconductor field effect transistors (MOSFETs)^[7,8] necessity for corrective actions required with diode,^[9,10] cumbersome measurements with cables (MOSFET, diodes),^[11] and non-suitability in patient dosimetry with plane-parallel ionization chamber (gold standard in electron beam dosimetry)^[12] persist the necessity to explore new dosimetric method for dosimetric verification.^[13] The dosimeters that are based on the luminescence properties

of solids are highly suitable for *in vivo* and in-phantom measurements as they are available in small sizes providing high spatial resolution and wider dose range coverage with high precision.^[14-16] Optically stimulated luminescence dosimeter (OSLD) has been introduced into radiation dosimetry, yet it is well known as a suitable dosimeter in space dosimetry and personal dosimetry over a decade.^[17-22] Despite the ability to measure small and large doses with high accuracy and precision, the drawback is that it has to be enclosed in a light-proof case owing to the nature of optically stimulated luminescence (OSL) phenomenon in the phosphor material ($\text{Al}_2\text{O}_3:\text{C}$).^[23] However, this drawback is easily overcome by encapsulating the

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sensitive element in a water equivalent light-tight plastic casing. A form factor difference of 50% with standard dot dosimeters enables to place this dosimeter in more restricted spaces, for instance, eyelid. The reported results of electron beam energy dependency with dot OSLD,^[24,25] optical fiber,^[19,26] and nanoDot^[27] was <1%. However, higher response of 1.9% was observed in the uncorrected data of electron beams with 6 MV photon beam.^[28] Schembri observed a discrepancy of 3.7% between electron (6–22 MeV) and 6 MV photon beams with OSL film.^[29] This significant difference points out the need for detailed investigations with careful attention to the experimental conditions. In addition, the other dosimetric responses with therapeutic electron beams such as field size, reproducibility, long-term fading effect, reader stability, and signal depletion per readout of nanoDot OSLD were studied, and the results were discussed.

MATERIALS AND METHODS

The OSLDs used were commercially available nanoDot dosimeters (Landauer, Inc., Glenwood, USA), and they are 5 mm diameter and 0.2 mm thick discs of Al₂O₃:C. These discs are encased in a 10 mm × 10 mm × 2 mm light-tight plastic case to prevent depletion of optical signals due to light. The bar code information in the nanoDot OSLD enables identification of each dosimeter and recording of the reading with ease. InLight microStar reader (Landauer Inc., Glenwood, USA) was used to read the optical signals of the OSLDs, with the reader warm up time of 10 min. The reader system includes an external PC, installed with a special software system to acquire the data, export to Microsoft Excel spreadsheet for analysis, and an optical annealing unit with recommended bleaching time of 6 h. During readout, OSLD is stimulated with a light of wavelength 540 nm, and the luminescence emitted is of wavelength 420 nm. The optically bleached OSLDs were read before irradiation, and the postirradiation readout was done after the transient signal decay. The resultant OSL counts reported were the difference between the pre- and post-irradiation optical signals of OSLD. The stability of the reader was checked before each readout session to ensure that the variations are within limits recommended by the manufacturer. With the intrinsic system check, reader stability was assessed by measuring the background counts (DRK) from photomultiplier tube (PMT), the counts from ¹⁴C (CAL), a small exempt source to indicate the consistency of the PMT and counts from PMT to check the stability of the beam intensity of the light-emitting diode. The values within the tolerance limit indicate the acceptable stability of the reader. In every measurement, four OSLDs were used and average of 4 readings of OSL counts represents each data point of the measurement. Unless stated otherwise, the precision in the measurements was <2% (1 σ).

The ionometric measurements were performed with a calibrated NACP-02 parallel plate ionization chamber developed by Nordic Association of Clinical Physicists. The chamber has a sensitive volume of 0.16 cm³, incorporated with

a front window of thickness 0.5 mm made of graphite covered with a mylar foil of 0.1 mm thickness as water proof. The dose 1 electrometer (Scanditronix Wellhofer AB, Sweden) of high precision is used along with the chamber and maintained at a polarizing voltage of 200 V. The ion chamber and electrometer were calibrated in absorbed dose to water according to TRS 398 reference dosimetry protocol in a Cobalt-60 beam. The data obtained with OSLDs was compared with ion chamber measurement wherever applicable.

Measurements with electron beams were performed in a Clinac DHX linear accelerator (Varian Medical Systems, Palo Alto, CA, USA). During irradiation, the dosimeters were placed at the reference depths [Table 1] corresponding to their electron energies (6, 9, 12, 16, and 20 MeV) with various electron applicators at 100 cm source to surface distance (SSD). The irradiations were done with a nominal dose rate of 400 MU/min and a known dose of 200 cGy was delivered for all dosimetric measurements unless otherwise mentioned. Measurements were carried out in plastic water phantoms made of white polystyrene material of size 30 cm × 30 cm with various thicknesses having a density of 1.04 g/cm³. The slabs of 10 cm thickness were used for backscatter in all irradiation set ups. A specially designed perspex slab with a groove arrangement was used to place OSLDs with minimized air gap during measurements.

RESULTS AND DISCUSSION

To ensure batch heterogeneity, element correction factor (ECF) for each OSLD (ratio of the average signal of the batch to the individual OSL signal) was calculated. For uniform irradiation, ⁶⁰Co beam was chosen to simultaneously irradiate the OSLDs to a known dose of 2 Gy at 5 cm depth with a field size of 20 cm × 20 cm. The histogram [Figure 1] shows the distribution of ECF values from 0.90 and 1.07 better than the reported distribution^[30] and a coefficient of variation <1.5%. This could be attributed to the improved production process of the supplier. Ninety percent of the dosimeters fall within 5% of the mean. The ECF obtained was applied to the raw readings of OSL in the successive uses in all measurements.

Figure 2 shows the dose response of OSLDs from 50 cGy to 1000 cGy with electron beams. The response was linear (with R² values ranging from 0.997 to 0.998) in the range from 50 cGy to 300 cGy above which supralinearity was observed up to 10 Gy, the maximum dose delivered. Similar behavior

Table 1: Reference depths for each energy level

Cone size (cm ²)	Reference depth (cm) for electron energies				
	6 MeV	9 MeV	12 MeV	16 MeV	20 MeV
6×6	1.27	1.97	2.80	3.67	4.51
10×10	1.27	1.97	2.80	3.70	4.68
15×15	1.28	1.97	2.78	3.70	4.69
20×20	1.26	1.98	2.78	3.69	4.69
25×25	1.28	1.97	2.80	3.70	4.69

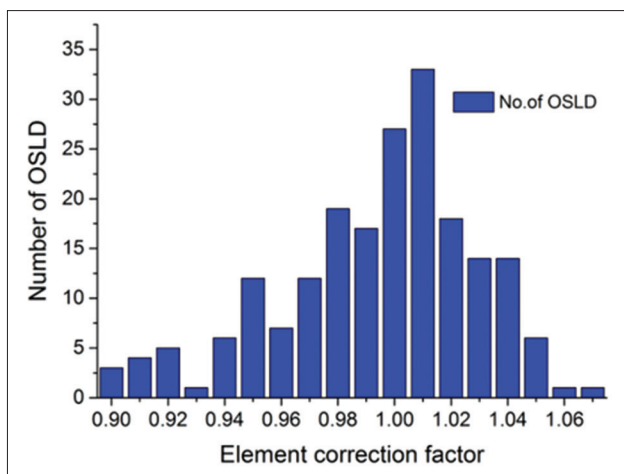


Figure 1: Histogram of the distribution of element correction factors of 200 optically stimulated luminescence dosimeters.

was observed for all five electron (6, 9, 12, 16, and 20 MeV) energies. As expected and evident, the supralinearity of OSLDs to therapeutic electron beam is similar to that of therapeutic photons beams at doses >2 Gy.^[7,24,25,29,31-33]

To establish the field size dependency, nanoDots were irradiated with electron applicators of 6 cm × 6 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm and 25 cm × 25 cm. A dose of 200 cGy was delivered by positioning the dosimeters at the reference depth of each energy level with 100 cm SSD. The measurement uncertainty was calculated, and it was found to be <1.5%. This indicates the independency of nanoDot response with field size. The results obtained suggest that OSLD can be used instead of ion chamber in the relative output factor measurement as there is no change in trend in the effect of OSL response compared to ion chamber.^[7] However, it may be noted that for 6 MV photon beams, Schembri and Heijmen^[29] reported a maximum discrepancy of 2.5% with the use of OSL, but there is no such study for electron beams. In addition, no dose rate dependence was observed for dose rates from 100 MU/min to 600 MU/min for a dose of 200 cGy delivered at the reference depths of electron energies with 15 cm × 15 cm electron cone applicator (SSD = 100 cm). Within the measurement uncertainty, this study confirms the dose rate independence of nanoDot OSLDs for the dose per pulse. Yukihiro *et al.*^[28] have also shown the dose rate variation of 1% in the response of OSL package of polyester film up to 1000 MU/min, with 9 MeV electron beam.

The variation in the energy response of OSL dosimeter was tested with five different electron energies of 6, 9, 12, 16, and 20 MeV and compared with 6 MV photon beams by delivering 200 cGy [Table 2]. A maximum variation of 2.1% was observed for 9 MeV electron when compared with 6 MV photon beam.

To investigate the reproducibility of OSLDs with repeated irradiations, the dosimeters were exposed to identical doses three times in three different ways. First, OSLDs were irradiated to a dose of 8 Gy with an increment of 2 Gy

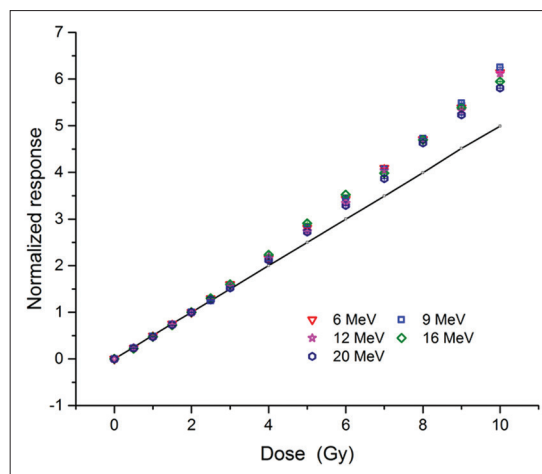


Figure 2: Dose response of nanoDot optically stimulated luminescence dosimeters with electron beams of different energies

Table 2: Variation in energy response of optically stimulated luminescence dosimeter

Energy (MeV)	Percentage variation in the response of nanoDot OSLD		Percentage of SD
	In comparison with 6 MV (%)	In comparison with 12 MeV (%)	
6	+2.0	+0.8	0.46
9	+2.1	+0.9	0.53
12	+1.2	-	0.43
16	+1.0	-1.0	0.37
20	+0.9	-1.0	0.48

Published results in comparison with 6 MV photon beams

Dunn <i>et al.</i>	A variation of 1.6±1.6% with nanoDot (20 MeV)
Yukihiro <i>et al.</i>	A variation of 1.9% with OSL films (6, 9,12, 16 and 20 MeV)
Schembri and Heijmen	A variation of 3.7% with OSL films (6-22 MeV)

OSLD: Optically stimulated luminescence dosimeter, SD: Standard deviation, OSL: Optically stimulated luminescence

and read after every exposure of 2 Gy with a minimum wait period of 10 min. The exposed OSLDs were optically bleached after each irradiation (bleach) and made ready for the next exposure. Second, the absorbed dose in the OSLDs was accumulated to a dose of 8 Gy in steps of 2 Gy without bleaching (accum) the dosimeters, and the OSLDs were readout. Third, OSLDs were irradiated to a dose of 8 Gy in a single session (SS), and the readout was done after the wait period. The OSLD irradiations were carried out with 6, 12, and 20 MeV electron beams at their corresponding reference depths in phantom with 15 cm × 15 cm applicator. Figures 3a-c show the response of dosimeters when they are bleached in between irradiations (bleach), accumulated the OSL signals without bleaching (accum), and irradiation of OSLD in a SS for 6, 12, and 20 MeV, respectively. The error bar represents the standard deviation of OSLD readings during readout. The accumulated response of OSLD was

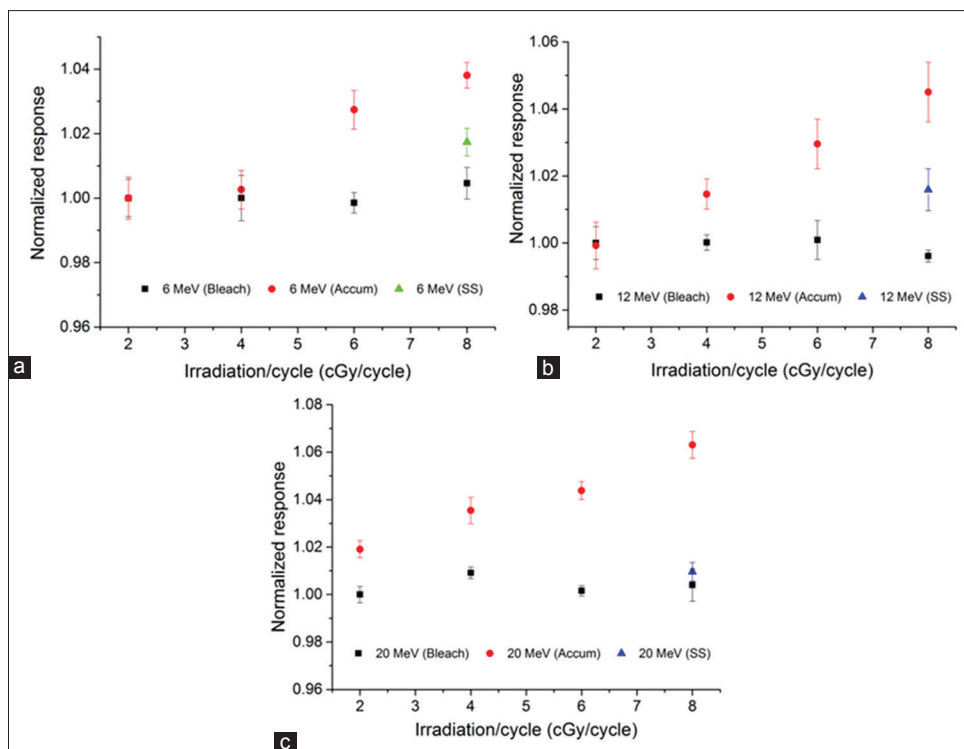


Figure 3: Reproducibility of optically stimulated luminescence dosimeters when irradiated to a total dose of 8 Gy with an increment of 2 Gy with bleach (bleach), without bleach (accum), and single session for (a) 6 MeV (b) 12 MeV (c) 20 MeV.

found to increase with dose and energy. The percentage difference observed between bleached and accumulated response was 3.9% in 6 MeV, 4.4% in 12 MeV, and 5.9% in 20 MeV electron beams at 8 Gy. The response variation of OSLDs due to accumulation of dose in an SS was found to be <2% with optically bleached OSLDs. A maximum difference of 7% with 6 MV photon beam was reported by Miller and Murphy.^[34] In our study, it has been noticed that the response of nanoDot OSLDs without accumulation of dose had shown no change in sensitivity. As the optical bleach extends the useful life of OSLD, it can be conveniently used multiple times eliminating the supralinear effect. A supralinear corrective action is required if the OSLDs are irradiated with high doses (HDs) more than 3 Gy or if the doses are accumulated without bleaching. However, the ability to optically reset and reuse the nanoDot OSLD is the extreme beneficial feature of this dosimeter in large scale dosimetry program where more than hundred OSLDs would be used.^[30]

The decay in OSL signal as a function of time was assessed by exposing nanoDot OSLDs to a low dose of 2 Gy and a HD of 10 Gy with 6, 9, 16, and 20 MeV electron beams at the reference depths with 100 cm SSD and an applicator size of 15 cm × 15 cm. The dosimeters were stored at room temperature and checked for the periods of (a) short-term (s/min/h), (b) mid-term (few days), and (c) long-term (months). OSLDs were read immediately after irradiation as early as 40 s, every day for the first 5 days, and then once a week for 5 weeks. The long-term fading was evaluated by taking OSLD reading

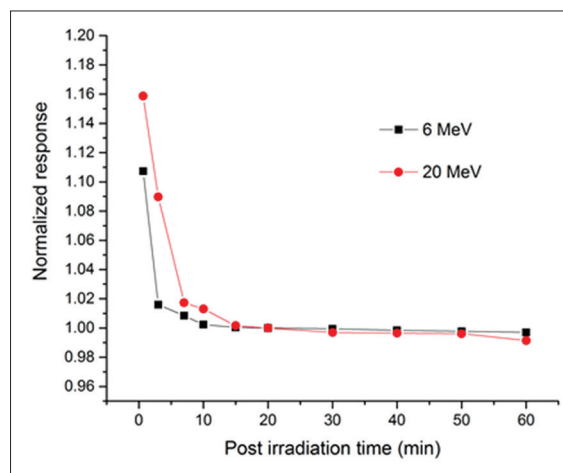


Figure 4: Post-irradiation fading of optically stimulated luminescence response from 40 s to 60 min following irradiation to 2 Gy of 6 MeV and 20 MeV electrons.

monthly once for about 8 months. Figure 4 shows the transient signal decay in OSL signal as a function of time with 6 and 20 MeV electron beams for 2 Gy. The rapid drop in the optical signal response due to the transient signal from the unstable electron traps depend on the energy of electrons. The drop in signal from 40 s to 20 min was found to be 10.7% for 6 MeV beam, whereas 15.9% for 20 MeV electron beams. It was evident from the graph that a minimum wait period of at least 10–15 min after the irradiation is required to achieve stable readout; accordingly, this was followed during all other measurements. The fading beyond 20 min post-irradiation was

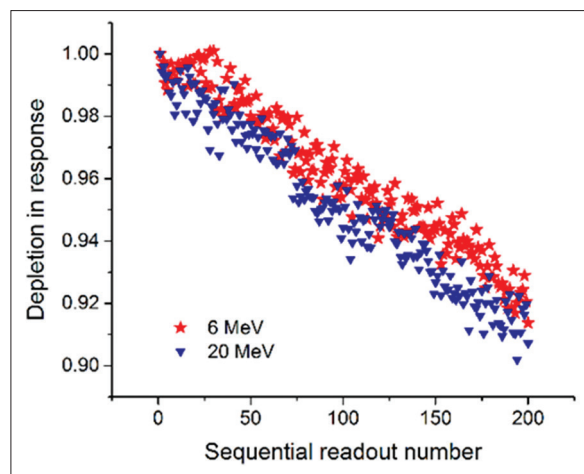


Figure 5: Depletion in response of optically stimulated luminescence dosimeters (irradiated to 2 Gy) during sequential readout (200 times) with 6 and 20 MeV electrons.

found to be similar (0.2%) for 6 and 20 MeV beams. The decay rate of fading stayed constant in every 1 month period (<1%), and the same effect was observed over a period of 8 months.

The signal loss during successive readout of OSL dosimeter was analyzed by exposing OSLDs to 2 Gy and 10 Gy of 6, 12, and 20 MeV electron beams (100 cm SSD) with 15 cm × 15 cm applicator at the reference depths. The OSLDs were read two hundred times successively, and the signal depletion per readout is shown in Figure 5. The percentage reduction in signal with electron beams of 6 MeV and 20 MeV for a dose of 200 cGy was 8.6%, and 9.3%, respectively. With a dose of 1000 cGy, the variation was 12.3% for 6 MeV and 15.8% for 20 MeV electron beams. These results indicate that the depletion rate depends on dose and energy involved during irradiation.

CONCLUSION

The electron beam energy dependence of nanoDot OSLDs was studied for the linearity of dose response, dose rate, field size, reproducibility, reader stability, fading characteristics, and depletion of signal per readout. Although negligible fading for post-irradiation storage from 20 min to several months, acceptable precision and linearity in the desired range, and high reproducibility make nanoDot dosimeters very attractive for the dosimetry of therapeutic electron beams, a note should be made for changes in sensitivity at doses beyond 3 Gy and electron beams energy dependence in reuse, short-term fading, and signal depletion on repeated readout.

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Conflicts of interest

There are no conflicts of interest.

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Dated: 20th March 2017

Hemant Manjrekar