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Chester S. Reft

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# The energy dependence and dose response of a commercial optically stimulated luminescent detector for kilovoltage photon, megavoltage photon, and electron, proton, and carbon beams

Chester S. Reft[a)]
*Department of Radiation and Cellular Oncology, University of Chicago, Chicago, Illinois 60637*

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Optically stimulated luminescent detectors, which are widely used in radiation protection, offer a number of potential advantages for application in radiation therapy dosimetry. Their introduction into this field has been somewhat hampered by the lack of information on their radiation response in megavoltage beams. Here the response of a commercially available optically stimulated luminescent detector (OSLD) is determined as a function of energy, absorbed dose to water, and linear energy transfer (LET). The detector response was measured as a function of energy for absorbed doses from 0.5 to 4.0 Gy over the following ranges: 125 kVp to18 MV for photons, 6–20 MeV for electrons, 50–250 MeV for protons, and 290 MeV/u for the carbon ions. For the low LET beams, the response of the detector was linear up to 2 Gy with supralinearity occurring at higher absorbed doses. For the kilovoltage photons, the detector response relative to 6 MV increased with decreasing energy due to the higher atomic number of aluminum oxide (11.2) relative to water (7.4). For the megavoltage photons and electrons, the response was independent of energy. The response for protons was also independent of energy, but it was about 6% higher than its response to 6 MV photons. For the carbon ions, the dose response was linear for a given LET from 0.5 to 4.0 Gy, and no supralinearity was observed. However, it did exhibit LET dependence on the response relative to 6 MV photons decreasing from 1.02 at 1.3 keV/$\mu$m to 0.41 at 78 keV/$\mu$m. These results provide additional information on the dosimetric properties for this particular OSL detector and also demonstrate the potential for their use in photon, electron, and proton radiotherapy dosimetry with a more limited use in high LET radiotherapy dosimetry. © *2009 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3097283]

Key words: optically stimulated luminescent detector, energy response, protons, LET

## I. INTRODUCTION

With the increasing complexity of radiation therapy delivery techniques such as intensity modulated radiation therapy to provide improved treatment plans while limiting the absorbed dose to normal tissues, there are increased challenges for the clinical medical physicist to obtain accurate *in vivo* and in-phantom dosimetric measurements. Not only may they require accuracy, high spatial resolution, and high sensitivity for measurements in both high and low dose regions, they may be also needed in a timely period. Thermoluminescent detectors (TLDs), diodes, MOSFETS, and film with their inherent advantages and disadvantages are currently used for these measurements. Optically stimulated radiation detectors (OSLDs) are a relatively new type of dosimeter for radiotherapy that are being investigated for applications in this field. Their radiation interaction mechanism is similar to thermoluminescence but utilizes light as opposed to heat to produce the radiation-induced luminescence. They originally evolved to measure the radiation exposure to occupationally exposed radiation workers, and they have largely replaced film in radiation badges.[1]

Aluminum oxide doped with carbon ($Al_2O_3:C$) is the material of choice for the OSLDs because of its high sensitivity[2] and relatively ease of fabrication.[3] Some of the potential advantages of these detectors for application in radiotherapy are minimal signal loss for repeated read-out measurements, a simpler read-out process using light instead of heat, stable signal after 8 min postirradiation, and optical bleaching to remove radiation-induced effects.[4] One disadvantage of these devices that differs from TLDs is that they accumulate a residual signal due to the filling of deeper energy traps that cannot be emptied by simply optical bleaching with fluorescent light. However, a small test dose of about 0.5 Gy can be used to evaluate changes in their sensitivity as discussed in Sec. II. OSLD introduction to radiotherapy has been constrained by the lack of information on their dosimetric characteristics for the megavoltage beams used in radiotherapy. However, this situation is rapidly changing with the increasing number of publications on their dosimetric properties. Aznar *et al.*[5] studied the real-time dosimetric properties of a prototype $Al_2O_3:C$ OSLD with dimensions of $0.1\times0.1\times0.2\ cm^3$. The detector was connected to an in-house read-out system via an optical fiber. Their measurements showed only a 0.6% difference in the detector response between 6 and 18 MV photons, a 0.3% variation in dose rate for 0.8–5.1 Gy/min, an angular dependence of about 1.3% from 45° to 320°, and less than a 1% change in response for field sizes from $5\times5$ to $15\times15\ cm^2$. Yukihara *et al.*[6] studied the dosimetric properties of commercially available (Landauer, Inc., Glenwood, IL) 0.3 cm thick polyester films containing $Al_2O_3:C$ powder. They reported the OSL response dependence on the dose rate, field size, and irradiation temperature to be less than 1%. They also reported no difference in the detector response for 6 and 18 MV photons, and their response was independent of the electron energy from 6 to 20 MeV, but was 1.9% lower than their response to 6 MV photons. Schembri and Heijmen[7] also investigated the radiation properties of similar $Al_2O_3:C$ films. They showed that their response was linear for doses from 0 to 2 Gy, exhibited little dose rate dependence, and for 6 MV photons, the field size and depth dependence were within ±2.5%. However, they reported a 4% difference in their response between 6 and 18 MV photons, and a 3.6% lower response for the electron beams relative to the 6 MV photons. Jursinic[4] published a very comprehensive study describing the dosimetric properties of a commercially available OSL detector encapsulated in a light-tight plastic holder that is read out with a simple and efficient system (Landauer, Inc., Glenwood, IL). He found their response to be independent of energy for megavoltage photons (6 and 15 MV) and electrons (6–20 MeV), and a 6% higher sensitivity to $^{192}$Ir gamma rays. He showed that the OSL signal stabilized after 8 min postirradiation and that they exhibited minimal orientation, dose rate, and temperature dependence, no sensitivity dependence to the dose per pulse, and a coefficient of variation in repeated exposures of 0.6%. Viamonte *et al.*[8] also investigated some dosimetric characteristics of the same OSLD and read-out system (Landauer, Inc., Glenwood, IL). They found the detector response to repeated exposures to be within 2.5%, no energy dependence for 6, 10, and 18 MV photons, but about a 4% lower response relative to $^{60}$Co gamma rays. Yukihara and McKeever[9] published a comprehensive review article on the fundamental and practical properties of optically stimulated luminescence dosimetry in medicine.

The purpose of this work is to provide a comprehensive evaluation of the dose response and energy dependence of a commercially available OSL detector (Landauer, Inc., Glenwood, IL) for kilovoltage photons, $^{60}$Co gamma rays, megavoltage photons, and electrons, protons, and carbon beams. As discussed previously, there are differences in the reported energy dependence of these detectors for megavoltage photon and electron beams. Data are also presented on their dose and energy response to protons for detectors irradiated at seven different facilities to investigate their potential applications in proton dosimetry. Since these detectors were sent via mail to the proton facilities, the feasibility of using them as "mailable" detectors for dosimetry measurements is discussed. The linear energy transfer (LET) dependence of the detectors was also studied by irradiating them in a carbon beam using various thicknesses of acrylic absorbers. Finally, the effectiveness of optically bleaching the detectors to remove their radiation damage to extend their useful life was investigated.

## II. MATERIALS AND METHODS

The OSLDs used in this study are 0.7 cm diameter, 0.02 cm thick, plastic disks containing $Al_2O_3:C$ encapsulated in a light-tight plastic holder with dimensions of $2.4\times1.2\times0.2\ \mathrm{cm}^3$. The sensitive diameter of the detector is 0.7 cm, and the plastic cover is $0.037\ \mathrm{g/cm}^2$ thick providing an effective depth of $0.07\ \mathrm{g/cm}^2$ for the point of measurement. They are available as inlight/OSL dot detectors, and they are read out with an inlight microstar reader (Landauer, Inc., Glenwood, IL) which operates in the continuous wave mode. In this mode the dosimeter is illuminated with a constant light source, while recording the stimulated luminescence in a 1 s illumination-read period. The optical stimulation was produced by a light emitting diode operating in conjunction with a colored glass bandpass filter producing a peak emission at 540 nm. The OSLD signal was measured by a photomultiplier tube filtered by a glass bandpasss filter providing a peak sensitivity at 420 nm. One particular advantage of these detectors is that the readout only samples a fraction of the signal so that it can be read multiple times to improve the measurement statistics. To remove the effects of irradiation, optical bleaching was utilized using a 22 W fluorescent lamp or a 150 W tungsten halogen lamp. For bleaching with the latter lamp, the OSLDs were positioned 2 cm distal from a focusing lens to prevent damage to the plastic encapsulation.

Each measurement in this study was the average of four consecutive detector readings. All the dosimeters were read out prior to and after irradiation and the difference is recorded. Although the vendor quotes a 2% variation in their relative sensitivities for a batch of dosimeters, measurements of their response exhibited about a 4% variation in their relative sensitivities. Therefore, to improve the measurement statistics, the relative sensitivity factors were obtained for each of the detectors used in this work by read out of their signal following an irradiation to 0.5 Gy. They were then optically bleached by illumination with a 22 W fluorescent lamp for approximately 24 h to remove the radiation effects of the 0.5 Gy irradiation. This procedure was repeated three additional times to obtain an average sensitivity factor for each detector that varied by less than 1% at 1 SD.

A Philips RT-250 provided photons from 125 to 250 kVp and a Varian Cl 2100 provided 6 and 18 MV photons as well as 6–20 MeV electrons. A Leksell Gamma Knife at Northwestern Memorial University Hospital provided $^{60}$Co gamma rays. Proton irradiations were performed at the following seven institutions: M.D. Anderson Proton Facility, Francis H. Burr Proton Therapy Center, University of Florida Proton Center, Institute Curie Proton Center (France), Paul Scherrer Institute (Switzerland), Loma Linda University Medical Center, and the National Cancer Center East (Japan). The carbon irradiation was performed at the National Institute of Radiological Sciences (Japan). The dosimeters were sent for irradiation to these facilities and returned via UPS or FedEx. They were read out and analyzed at our institution. For the kilovoltage irradiations, the detectors were placed on the surface of a solid water (RMI 451) phantom, while for the megavoltage x rays and electron irradiations, they were po-

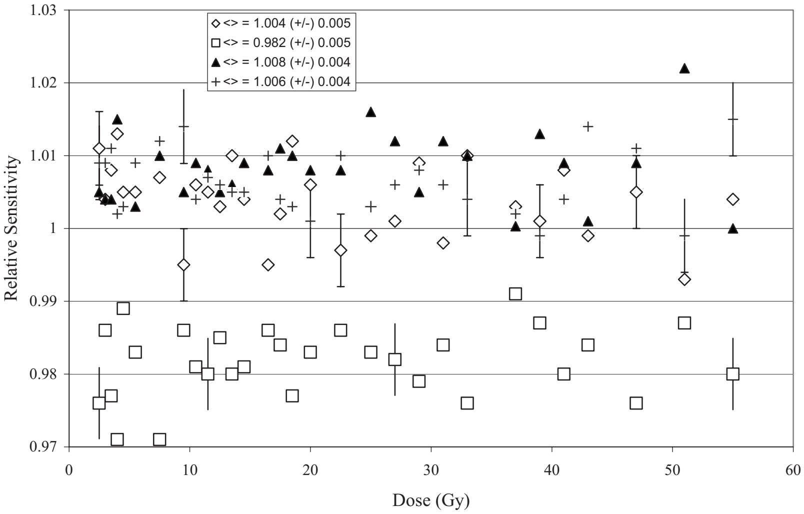

FIG. 1. The variation in the relative sensitivities to accumulated absorbed dose for four randomly selected OSLDs. The detectors were optically bleached prior to each subsequent irradiation and read out.

sitioned at 10 cm depth and $d_{\max}$, respectively. For the megavoltage photon and electrons, the irradiations were performed in both solid water and water phantoms because published results[10] showed there are differences in the water equivalence of the various solid water materials. For this comparison, a set of detectors was sealed in water tight plastic envelopes, and a set of unsealed detectors was irradiated in water at a depth of 10 cm and $d_{\max}$ for the photon and electron beams, respectively. Their measured signals were compared to a set of detectors positioned at the same depths in solid water and irradiated under identical conditions. For the irradiation with $^{60}$Co of the Gamma Knife, single detectors were placed at the center of an 8 cm diameter polystyrene sphere, which was positioned at the isocenter of the unit. A 1.8 cm diameter helmet was used for these irradiations. For the proton irradiations, they were positioned at the center of the spread-out-Bragg peak (SOBP) except where otherwise noted. For the proton irradiations, the phantom materials containing the OSLDs were solid water, Plexiglas, polystyrene, and polyethylene. The absorbed dose to water was obtained by correcting by the ratio of mass stopping powers of the materials to water. The detectors were placed on the surface of the phantom for the carbon irradiations and the irradiations were performed with a carbon beam of 290 MeV/u. The LET was varied by using different thicknesses of acrylic absorbers. Each measurement reported is the average of at least three separate dosimeters.

An Exradin A12 ionization chamber with calibration factors from an Accredited Dosimetry Calibration Laboratory (ADCL at University of Wisconsin) was used to measure the absorbed dose for the photon and electron irradiations. Output calibration for the kilovoltage irradiations was performed in air following the TG 61 AAPM protocol.[11] The effective kilovoltage energies for these beams were determined from narrow beam half-value layer measurements. Although air kerma calibration factors $N_k$ were only obtained for 50 and 100 keV from the ADCL for the ionization chamber, Borg *et al.*[12] showed that the response of the A12 ionization chamber varied by only about 4% from 30 to 200 keV. This variation in energy response of the chamber was accounted for by including an additional 3% uncertainty in the data analysis. The output calibration of the linear accelerator for the megavoltage photons and electrons was performed following the TG 51 AAPM protocol.[13] The output of the Gamma Knife was calibrated using an Exradin A14 ionization chamber with an $N_k$ calibration factor from an ADCL. The chamber was placed at the center of an 8 cm diameter polystyrene sphere, which was positioned at the isocenter of the unit. The dose was determined by converting the measured dose to air to dose to water via the ratio of mass energy absorption coefficients. The proton and carbon beams were calibrated at the individual facilities following the TRS-398 IAEA protocol.[14]

The energy response of the detectors defined as $F^{Q}_{6\ \mathrm{MV}}$ for a given radiation beam of quality $Q$ relative to 6 MV x rays is given by

$$F^{Q}_{6\ \mathrm{MV}} = [\mathrm{OSL}(Q)/D_{\mathrm{wat}}(Q)]/[\mathrm{OSL}(6\ \mathrm{MV})/D_{\mathrm{wat}}(6\ \mathrm{MV})],$$

where $\mathrm{OSL}(Q)/D_{\mathrm{wat}}(Q)$ is the light output per absorbed dose in water for beam quality $Q$ and $\mathrm{OSL}(6\ \mathrm{MV})/D_{\mathrm{wat}}(6\ \mathrm{MV})$ is the light output per absorbed dose in water for 6 MV x rays.

## III. RESULTS

### III.A. Sensitivity, linearity, and luminescence stability

Figure 1 summarizes the variation in the relative sensitivities of four randomly selected detectors to increasing absorbed dose. These data were obtained for various dose increments of 0.5–4.0 Gy up to an accumulated dose of 55 Gy. The detectors were optically bleached prior to each subsequent irradiation and read out. The individual relative sensitivity, $s_i = \langle \mathrm{OSLD} \rangle / \mathrm{OSLD}_i$, where $\langle \mathrm{OSLD} \rangle$ is the average reading of the four detectors and $\mathrm{OSLD}_i$ is the reading of an individual detector, was obtained for each detector following irradiation. Figure 2 shows the averaged detector response per absorbed dose to an accumulated absorbed dose of 60 Gy for the same four detectors for 6 MV photons; the data are normalized to their response at 1 Gy. Figures 3 and 4 illus-

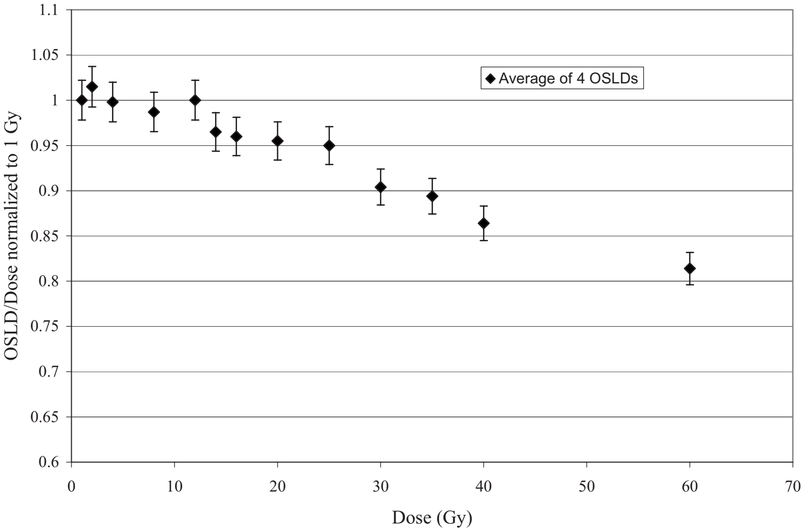

FIG. 2. The averaged detector response per absorbed dose for the same four randomly selected detectors in Fig. 1. The data are normalized to their response at 1 Gy for the 6 MV photons.

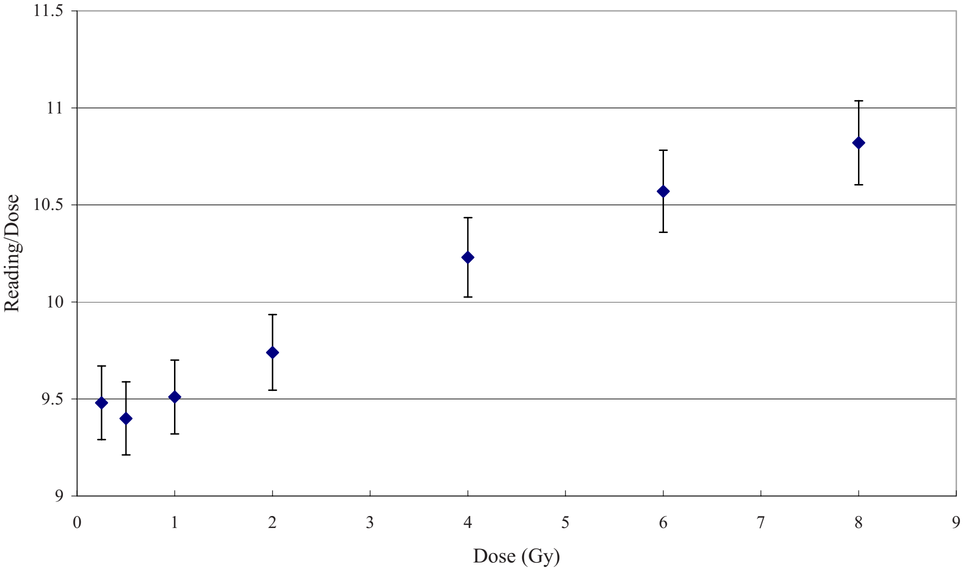

FIG. 3. The OSLD response per absorbed dose versus dose for the 6 MV photons for a typical detector.

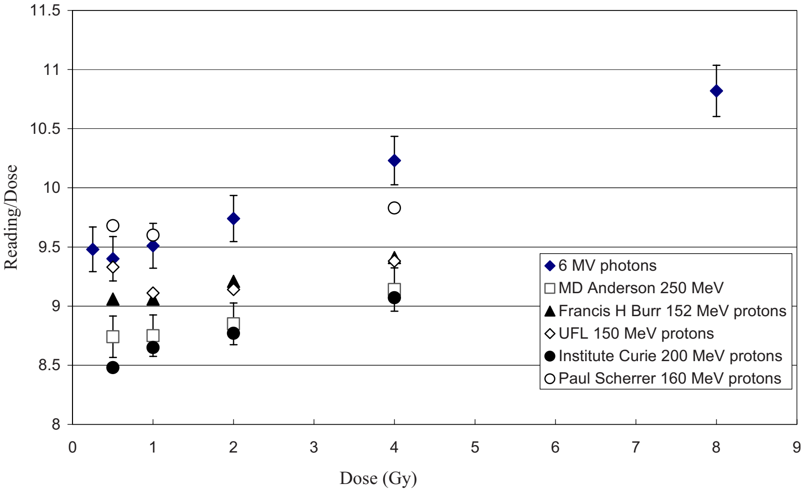

FIG. 4. The OSLD response per absorbed dose versus dose for the 6 MV photons and representative proton irradiations.

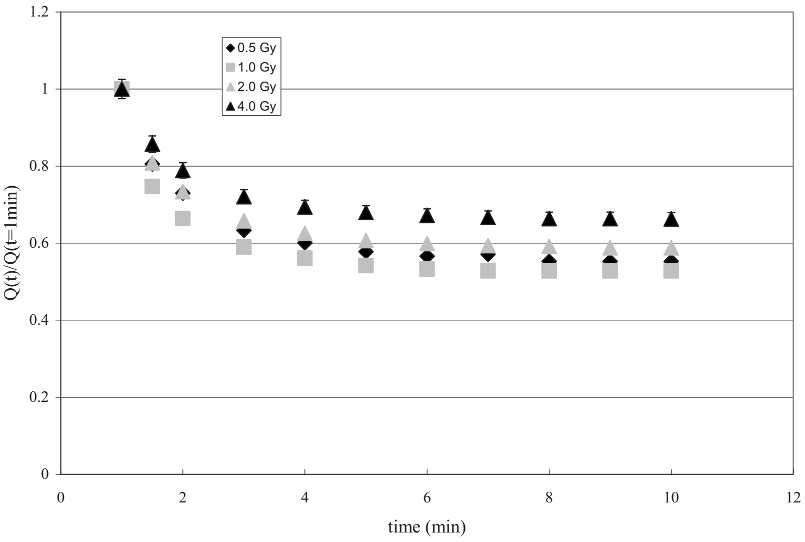

FIG. 5. The decay of the OSLD signal with time at room temperature following irradiation. Each data point is the average response of three individual detectors for a group of four irradiated to the selected absorbed doses. The data are normalized to their response one minute postirradiation.

trate their response per dose to 6 MV photons and representative proton beams, respectively. Similar results were obtained for the kilovoltage and electron beams. Figure 5 presents the room temperature signal decay with time postirradiation with 6 MV photons for 12 individual detectors. Four sets of three separate detectors were irradiated to absorbed doses of 0.5, 1.0, 2.0, and 4.0 Gy, respectively. The data points are the average of the three detectors normalized to their signal measured 1 min postirradiation.

### III.B. Energy response

Table I summarizes the dose response of the detector to the various photon and electron beams normalized to their response to 1 Gy of the 6 MV photons. For the megavoltage photons and electrons, the irradiations were performed in both solid water and water phantoms to investigate the difference in detector response in the two media. Table II summarizes the results for the proton irradiations at the different facilities. The data are normalized to the detector response to 1 Gy for the 6 MV photons. The detectors were all irradiated at the center of the SOBP except for the irradiation at facility F′, where they were also irradiated in the plateau region of the proton beam. Table III summarizes their dose response and energy dependence for protons.

### III.C. LET dependence

The LET dependence of the detectors is summarized in Fig. 6 which shows their response per dose as a function of LET for various absorbed doses for the carbon beam where the data are normalized to the detector response to 1.0 Gy of

TABLE I. Energy response of OSLD normalized to their response at 6 MV for 1 Gy, $F^{Q}_{6\text{ MV}}=(\text{OSL}/\text{Dose})^{Q}_{6\text{ MV}}$.

| Modality | Beam quality | Equivalent energy[a] (MeV) | OSLD[b] solid water | OSLD[c] $H_2O$ |
|---|---|---|---|---|
| Photons | 125 kVp | 0.035 | 3.55(3.25)[d] | |
| | 150 kVp | 0.057 | 3.05(2.96) | |
| | 200 kVp | 0.074 | 2.20(2.60) | |
| | 250 kVp | 0.110 | 1.71(1.60) | |
| | ⋯ | 1.25[e] | 1.045(1.01) | |
| | 6 MV | 2.4 | 1.00(1.00) | 1.00 |
| | 18 MV | 5.7 | 0.99(0.986) | 0.99 |
| Electrons | ⋯ | 6 | 0.96 | 0.99 |
| | ⋯ | 9 | 0.97 | 0.99 |
| | ⋯ | 12 | 0.96 | 0.98 |
| | ⋯ | 16 | 0.97 | 0.98 |
| | ⋯ | 20 | 0.97 | 0.98 |

[a] Equivalent energy is the energy of a monoenergetic photon beam having the same measured HVL as the given beam.
[b] $\sigma \approx \pm 5.5\%$ and $\pm 3.8\%$ within 1 SD for kilovoltage and megavoltage irradiations, respectively.
[c] $D(\text{SW})/D(\text{H}_2\text{O}) \approx 0.99$.
[d] Values within parentheses are from Monte Carlo calculations (Ref. 20).
[e] $^{60}$Co from Gamma Knife unit.

TABLE II. OSL response as a function of dose for a 6 MV photon beam and seven proton beams normalized to 1 Gy for 6 MV photons. The estimated measurement uncertainties are ±4.2% (1 SD): A, University of Chicago; B, M. D. Anderson; C, Francis H. Burr Proton Therapy Center; D, University of Florida; E, Institute Curie; F, Paul Scherrer Institute, F′ irradiated in plateau region; G, National Cancer Center, Kashiwa; and H, Loma Linda University Medical Center.

| Dose (Gy) | Phantom material | A, 6 MV, Solid water | B, 250 MeV, Solid water | C, 152 MeV, Plexiglas | D, 150 MeV, Solid water | E, 200 MeV, Plexiglas | F, 160 MeV, Plexiglas | F′, 160 MeV, Plexiglas | G, 160 MeV, Polyethylene | H, 200 MeV, Polystyrene |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | | 1.00 | 1.06 | 1.05 | 1.07 | 1.06 | 1.03 | 1.05 | 1.02 | 1.03 |
| 1.0 | | 1.00 | 1.07 | 1.05 | 1.06 | 1.08 | 1.02 | 1.06 | 1.06 | 1.03 |
| 2.0 | | 1.02 | 1.07 | 1.07 | 1.06 | 1.09 | | | 1.07 | 1.07 |
| 4.0 | | 1.08 | 1.10 | 1.09 | 1.09 | 1.12 | 1.06 | 1.05 | 1.09 | 1.09 |

TABLE III. Energy response of OSL detectors to protons for 1 Gy absorbed dose normalized to their response to 1 Gy of the 6 MV photons. The detectors were located on the surface of a Plexiglas phantom and the irradiations were performed at Francis H. Burr Proton Therapy Center. The estimated measurement uncertainties are ±4.2% (1 SD).

| Energy (MeV) | $dE/dx$ (keV/$\mu$m) | $(\mathrm{OSL/Dose})^{E}_{6\ \mathrm{MV}}$ |
|---|---|---|
| 47 | 1.33 | 1.02 |
| 108 | 0.69 | 1.02 |
| 139 | 0.58 | 1.02 |
| 170 | 0.50 | 1.01 |

the 6 MV photons. For these irradiations, the detectors were positioned at the surface of the phantom. The effective depth of measurement of the detector in this configuration is about 0.07 $\mathrm{g/cm^2}$, which is just beyond the buildup region for these beams.

## IV. UNCERTAINTY ANALYSIS

The uncertainties in these measurements are due to the variation in the individual detector sensitivities and the calibration of the various beam qualities used in this study. From repeated irradiation and read out of the detectors, an uncertainty of 1% (1 SD) was assigned to the individual detector sensitivities. The AAPM protocol[11] on kilovoltage radiotherapy estimates a 3.6% uncertainty in the output. In this study ionization chamber calibration factors at two beam qualities were used. However, published data[12] for the A12 chamber showed that its response varied by only 4% over the energies of interest in this work. To account for the energy dependence in the ionization chamber calibration factor, an additional 3% was included in the estimation of the output uncertainty resulting in a 4.7%, $[(3.6\%)^2+(3.0)^2]^{1/2}=4.7\%$, uncertainty in the kilovoltage dose. For the megavoltage photon and electron dose calibrations, a 2.5 % uncertainty was assigned. The proton and carbon radiation facilities follow the TRS 398 dosimetry protocol which estimates a 3% uncertainty in the dose. The estimated uncertainty in the quantity $F^{Q}_{6\ \mathrm{MV}}$ is obtained by adding in quadrature the individual uncertainties. For the kilovoltage measurements, the estimated uncertainty is 5.5% attributed to the uncertainties in OSL sensitivity (1%), kilovoltage dose (4.7%), and 6 MV dose (2.5%). For the megavoltage photon and electron measurements, the estimated uncertainty is 3.8% attributed to the uncertainties in OSL sensitivity (1%), photon and electron dose (2.5%), and 6 MV dose (2.5%). For the proton and carbon measurements, the estimated uncertainty is 4.2% attributed to the uncertainties in OSL sensitivity (1%), proton and carbon dose (3%), and 6 MV dose (2.5%).

## V. DISCUSSION OF RESULTS

The variation in the individual radiation sensitivity of four randomly selected detectors is presented in Fig. 1, while in Fig. 2 their measured dose response versus accumulated absorbed dose is shown. The data in Fig. 1 demonstrate the constancy of the relative sensitivities of these detectors up to

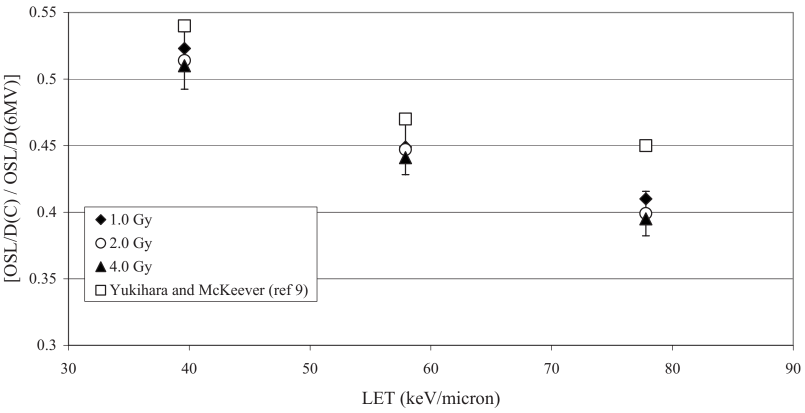

FIG. 6. The OSLD absorbed dose response in a carbon beam illustrating the LET and dose dependence. The data are normalized to the OSLD response to 1 Gy for the 6 MV photons. The estimated measurement uncertainties are ±4.2%.

an accumulated absorbed dose of 55 Gy. Published data,[4,9,15–17] as well as the data presented in Fig. 2, show that at about 20 Gy of accumulated dose, the detector sensitivity begins to decrease by about 4%/10 Gy. These results demonstrate that even though the sensitivity of the individual detectors decreases above 20 Gy, the relative sensitivities of a selected group of these detectors remain constant within about 0.5% at absorbed doses greater than 20 Gy. The dose response of a typical detector presented in Figs. 3 and 4 exhibit good linearity up to 2.0 Gy with supralinearity occurring at higher absorbed doses. This behavior, which is similar to thermoluminescent detectors (TLD 100), has been reported in literature.[4–8] Figure 4 shows the response per dose of the detectors as a function of absorbed dose for the 6 MV and proton irradiations. Again the measured dose response shows linearity up to 2.0 Gy and supralinearity at higher absorbed doses. The proton dose response exhibits similar behavior except that the supralinearity effect is smaller.

Figure 5 shows the room temperature decay of the OSL signal postirradiation for four sets of detectors irradiated to different absorbed doses. Each data point is the average of three separate detector measurements, and they are normalized to the measured signal at 1 min postirradiation. These results are in good agreement with the published data[4] that showed an initial rapid decay of the signal, followed by a stabilization of the signal after about 8 min. Although not shown in the figure, measurements were taken out to 11 days to investigate the slowly decaying signal. Measurements from 10 min out to 11 days showed that the decaying signal could be fitted with an exponential with a decay constant of $\lambda \approx 1.1\times 10^{-4}$ h$^{-1}$ or about 0.3% signal loss per day. For absorbed doses from 0.5 to 2.0 Gy, the relative measured detector signals, $Q(t=10\ \text{min})/Q(t=1\ \text{min})$, approach the same value of 0.56, whereas for 4.0 Gy, the relative signal stabilizes at a higher value of 0.66. A possible explanation is that for the higher absorbed doses where supralinearity begins there is a residual radiation-induced signal due to the filling of deeper traps in the detector. This is supported by other measurements showing that optical bleaching of the detectors with a 22 W fluorescent light resulted in a greater background signal in the detectors irradiated to 4.0 Gy than those irradiated to lower absorbed doses. To investigate the effectiveness of optical bleaching to remove the irradiation-induced detector signal, detectors were irradiated to absorbed doses of 0.5, 1.0, 4.0, and 8.0 Gy, and then optically bleached with a 22 W fluorescent light. The results showed that for absorbed doses up to 2.0 Gy, optical bleaching eliminated essentially all their signals without changing their relative sensitivities. This suggests that their useful life could be extended beyond a total absorbed dose of 20 Gy by postirradiation optical bleaching. However, for absorbed doses greater than 2.0 Gy where supralinearity begins, optical bleaching with fluorescent light removes most but not the entire radiation-induced signal. For dosimeters irradiated to absorbed doses of 4.0 and 8.0 Gy, optical bleaching removed about 99.9% of their radiation-induced signal reducing it to 2.0 and 2.7 times their preirradiation values, respectively. This suggests that dosimeters irradiated to the higher absorbed dose accumulate a residual signal due to the filling of deeper energy traps, which are related to the magnitude of

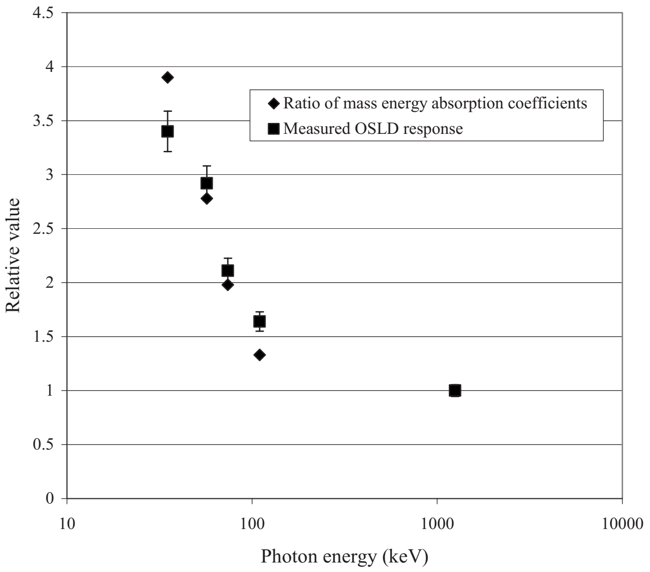

FIG. 7. A plot of the ratio of mass energy absorption coefficients of Al$_2$O$_3$ to water normalized to their values at $^{60}$Co from Ref. 19 along with the measured OSLD response data from Table I normalized to their response at $^{60}$Co for the kilovoltage energies used in this study. This figure shows that the ratio of mass energy absorption coefficients suggested by Attix (Ref. 18) provide a good approximation of the OSLD response at kilovoltage energies.

the supralinearity that cannot simply be removed by optical bleaching with fluorescent light. However, optical bleaching for about three minutes with a tungsten halogen lamp which has higher energy photons essentially emptied the traps removing the residual OSL signal.

The kilovoltage energy response of the OSL detectors is summarized in Table I. The data are normalized to their response to 1 Gy of the 6 MV photons. The increased response at lower energies is attributed to the increased photoelectric effect in the aluminum oxide, $Z(\mathrm{Al_2O_3})=11.2$. As described by Attix,[18] the energy response of a homogeneous dosimeter can be estimated by calculating its ratio of mass energy absorption coefficient relative to water at the two energies provided certain conditions are satisfied. Here, this requires transient charge particle equilibrium in the OSLD which occurs in the detectors at the kilovoltage energies. In Fig. 7 the ratio of mass energy absorption coefficients of $\mathrm{Al_2O_3}$ to water[19] is plotted along with the measured OSLD response data from Table I at the kilovoltage energies. The data are normalized to the ratio of mass energy absorption coefficient of $\mathrm{Al_2O_3}$ to water at $^{60}$Co. This figure shows that the Attix equation provides a good approximation of the measured OSLD response at kilovoltage energies. For clinical use the measured OSLD response data would be used. The values in the parentheses of column 4 are Monte Carlo calculations of the energy response of aluminum oxide detectors in kilovoltage beams.[20] Within the experimental uncertainties, the measurements are in reasonable agreement with the calculated values.

The energy response of the detectors to megavoltage photons and electrons is also presented in Table I. The results for $^{60}$Co show a 4.5% greater sensitivity relative to 6 MV for these detectors. This agrees with the measurement reported by Viamonte *et al.*[8] who found a 4.5% greater sensitivity for $^{60}$Co relative to the 6 MV photons. No measurable difference in response was found between 6 and 18 MV photons. This result is consistent with those reported in literature[4,5,8] that there was no energy dependence in detector response for photons irradiated with energies between 6 and 18 MV. While Schembri and Heijmen[7] reported a 4% difference in the detector response between 6 and 18 MV photons. Note that the data in Table I for the 6 and 18 MV photons are the same for the measurements in both water and solid water phantoms. It should be pointed out that there was no difference in the detector response between the sealed and the unsealed detectors in water. This shows that they can be irradiated in water without any deterioration in response. For the electron irradiations the results show that within the measurement uncertainties there is no energy dependence between the electrons and photons. This agrees with the results reported by Jursinic[4] who also did not find any energy dependence for 6 and 15 MV x rays and 6–20 MeV electrons. The energy independence for electrons is also supported by the mass collision stopping power ratios of $\mathrm{Al_2O_3}$ to water[19] which varies by only 2.5% from 1 to 20 MeV. However, Schembri and Heijmen reported a 3.6% lower response for electrons relative to 6 MV photons, although differences among the various electron beam energies were not significant. This difference could be due to the differences in the phantom materials used in the irradiations, polystyrene compared to water and solid water. Energy dependent fluence correction factors are required to convert the dose to polystyrene to the dose to water.[21] This difference is illustrated by the data in columns 4 and 5 in Table I for irradiations in solid water compared to those in water. The results exhibit about 3% lower response relative to the 6 and 18 MV photons measured in solid water. As described by Tello *et al.*,[10] there are differences in the water equivalence of the various phantom materials. Using their corrections for solid water to water media to correct the measurements in solid water, the OSL response to megavoltage photons and electrons agrees within the estimated measurement uncertainties.

The response of the OSL detectors to the proton irradiations at the various facilities is summarized in Table II. The phantom materials that the detectors were irradiated in at the various facilities are also presented in this table. It should be noted that the dose rate for the detector irradiations at the institutions varied from 2.0 to 7.0 Gy/min which could affect a comparison of the results. However, published data for these detectors showed their response to be independent of the dose per pulse[4] and monitor unit rate[5,8] for megavoltage photons. Thus, it is reasonable to assume a similar behavior for protons, and therefore, the measurements should be independent of the dose rate at the proton facilities. The data are normalized to the response of the detector to 1.0 Gy of the 6 MV photons. All the data were obtained for the detectors irradiated in the SOBP except for the data in column F′ where they were irradiated in the plateau region of the proton beam. These results demonstrate that within the measurement uncertainties their response is independent of the proton energy and is about 6% greater than their response to 6 MV photons. The energy independence is supported by the data in Table III which shows their response normalized to the 6 MV photons as a function of proton energy to be independent of energy. It is also supported by the data in columns F and F′ where the detectors were irradiated in both the SOBP and the plateau region. Although the proton energy spectrum is expected to be different in these regions, the detector response is the same. This table also shows that their response is independent of changes in LET from 0.50 to 1.33 keV/$\mu$m. For the proton irradiations, the dosimeters were sent to and from the institutions by mail. The consistency of the data from the different institutions supports the feasibility of using these detectors as mailable detectors for various dosimetric measurements such the intercomparison of therapy machine calibrations and *in vivo* dosimetry. Finally, as shown in Fig. 4, their response per dose as a function of absorbed dose for protons is very similar to that for 6 MV photons except that the supralinearity effect is smaller. This in agreement with Sawakuchi *et al.*[22]

Figure 6 summarizes the measured detector response to carbon irradiation. The results exhibit a large LET dependence with their response decreasing by a factor of 2.5 for LET changes from 0.5 to 78 keV/$\mu$m. Also shown in the figure for comparison are the data published by Yukihara and McKeever[9] on the LET dependence of $\mathrm{Al_2O_3{:}C}$ Luxel dosimeters relative to the gamma radiation. Their data are in good agreement with those reported here for the carbon irradiations. For protons with a LET of about 1.0 keV/$\mu$m, they reported a dose response of 1.11 relative to the gamma radiation compared to a dose response of 1.06 measured in this study. The response of many solid state detectors changes with LET. In particular TLDs exhibit various degrees of LET dependence.[23] For example, the response of LiF TLDs relative to $^{60}$Co varies from 0.90 to 0.40 over the range of LET from 10 to 100 keV/$\mu$m, whereas $LiB_4O_7$:Mn varies by only 14% over the same LET range.[24] Since the radiation interaction processes for thermoluminescence and optically stimulated luminescence are very similar, one would expect a LET dependence for the OSL dosimeters. Although these detectors have a strong LET dependence, for a given LET their response is linear with dose from 1 to 4 Gy with no observable supralinearity, as illustrated in Fig. 6. This is consistent with the results published by Sawakuchi *et al.*[22] As pointed out by Cameron *et al.*[25] for LiF TLDs, supralinearity and sensitization are both related to the LET of the radiation, and supralinearity only becomes evident at the higher absorbed doses for high LET particles.

## VI. CONCLUSIONS

In this study a number of dosimetric characteristics of OSL detectors were investigated. Some of the results verify published results that were obtained for the megavoltage photon and electron irradiations such as the rapid initial signal decay following irradiation, dose linearity up to 2 Gy, and supralinearity at higher absorbed doses. The response of the detectors was studied as a function of energy and absorbed dose for photons with energies from 125 kVp to 18 MV. Their response relative to the 6 MV photons increases from 1.05 for $^{60}$Co to 3.5 for x rays with an equivalent energy of 35 keV. For the 6 and 18 MV photons and 6–20 MeV electrons, their response was independent of the beam quality. For proton irradiations, their response was found to be independent of energy and about 6% greater than their response to 6 MV photons. Relative to the 6 MV photons, smaller supralinearity was found which was possibly due to the slightly higher LET of the protons. The detectors exhibited a strong dependence on LET. For the carbon irradiation their response relative to the 6 MV photons varied from ~0.40 to ~0.50 for LETs of 78–40 keV/$\mu$m. No supralinearity was observed for the carbon irradiations over the 1–4 Gy dose range in this study. This is consistent with this effect being inversely related to the LET of the irradiation. The consistent results for the proton irradiations at the different facilities demonstrate their potential for use as mailable dosimeters for intercomparison of the output of therapy machines. Finally, it was found that optical bleaching of detectors irradiated to absorbed doses of 2 Gy or less could remove the irradiation-induced signal, thus extending their useful life beyond 20 Gy.

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[a] Electronic mail: creft@radonc.uchicago.edu

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