Optically stimulated luminescence (OSL) of carbon-doped aluminum oxide (Al_2O_3:C) for film dosimetry in radiotherapy

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Introduction and Purpose: Conventional x-ray films and radiochromic films have inherent challenges for high precision radiotherapy dosimetry. Here we have investigated basic characteristics of optically stimulated luminescence (OSL) of irradiated films containing carbon-doped aluminum oxide (Al_2O_3:C) for dosimetry in therapeutic photon and electron beams. *Materials and Methods:* The OSL films consist of a polystyrene sheet, with a top layer of a mixture of single crystals of Al_2O_3:C, ground into a powder, and a polyester base. The total thickness of the films is 0.3 mm. Measurements have been performed in a water equivalent phantom, using 4, 6, 10, and 18 MV photon beams, and 6–22 MeV electron beams. The studies include assessment of the film response (acquired OSL signal/delivered dose) on delivered dose (linearity), dose rate (1–6 Gy/min), beam quality, field size and depth (6 MV, ranges 4×4–30×30 cm^2, d_{max}–35 cm). Doses have been derived from ionization chamber measurements. OSL films have also been compared with conventional x-ray and GafChromic films for dosimetry outside the high dose area, with a high proportion of low dose scattered photons. In total, 787 OSL films have been irradiated. *Results:* Overall, the OSL response for electron beams was 3.6% lower than for photon beams. Differences between the various electron beam energies were not significant. The 6 and 18 MV photon beams differed in response by 4%. No response dependencies on dose rate were observed. For the 6 MV beam, the field size and depth dependencies of the OSL response were within ±2.5%. The observed inter-film response variation for films irradiated with the same dose varied from 1% to 3.2% (1 SD), depending on the measurement day. At a depth of 20 cm, 5 cm outside the 20×20 cm^2 6 and 18 MV beams, an over response of 17% was observed. In contrast to GafChromic and conventional x-ray films, the response of the Al_2O_3:C films is linear in the clinically relevant dose range 0–200 cGy. *Conclusions:* Measurement of the OSL signal of irradiated films containing Al_2O_3:C is a promising technique for film dosimetry in radiotherapy with no or small response variations with dose rate, beam quality, field size and depth, and a linear response from 0 to 200 cGy. © *2007 American Association of Physicists in Medicine*. [DOI: 10.1118/1.2737160]

Key words: optically stimulated luminescence, aluminum oxide, radiotherapy film dosimetry

I. INTRODUCTION

Optically stimulated luminescence (OSL) arises from optical stimulation of minerals that have been previously exposed to ionizing radiation. During exposure, the absorbed energy is partially transferred to charges (electrons and holes) within the volume of the detector. A fraction of these charges immediately looses its energy by emitting radioluminescence light. Other carriers are trapped at pre-existing or radiation induced defect sites in the crystal lattice of the detector, where they can remain for indeterminate periods of time. During optical stimulation with light the trapped charges can be liberated and a fraction of these recombine, and release energy consisting of luminescence light, due to electronic transitions at recombination (luminescence) centers. The electron population in the traps is the result of irradiation of the material, and thus the OSL intensity is related to the absorbed radiation dose.[1]

OSL materials operate much the same way as thermoluminescence (TL) phosphors, except that the recombination luminescence is stimulated optically rather than thermally. Many luminescence materials popular in TL dosimetry suffer from thermal quenching, the loss of luminescence efficiency as the temperature of the material is increased. The TL sensitivity (light output per unit absorbed dose) is dependent on the heating rate, with higher heating rates leading to greater loss of sensitivity. Stimulating the luminescence using light and recording the emission at room temperature—at which the luminescence efficiency has a maximum—results in an increase of approximately an order of magnitude in the sensitivity of luminescence emission for OSL compared with TL. Thus, OSL dosimetry avoids problems caused by heating of TL dosimeters.[2] OSL may suffer from a phenomenon called laser quenching, but this effect can be avoided by using not too high intensity light sources for stimulation.[1]

Currently applied film dosimetry in radiotherapy, based on conventional x-ray or radiochromic films, has well-known inherent challenges, such as energy dependence, nonlinear dose response, fading, polarization effects, etc. On the other hand, OSL has found a widespread application in a variety of radiation dosimetry fields, including personal monitoring,[3] environmental monitoring,[4] retrospective dosimetry used in

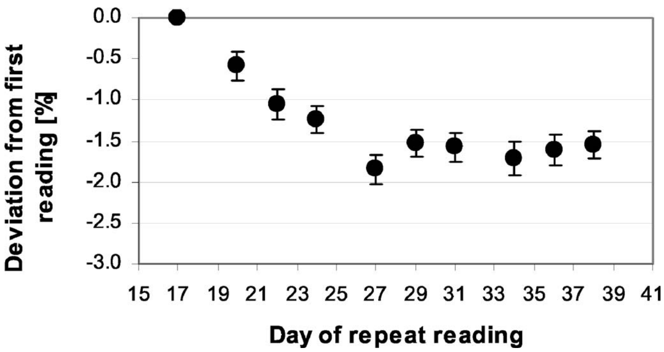

FIG. 1. Fading of the OSL signal in a three week period. Deviations [%] of repeat readings from the first reading. The error bars represent 95% confidence intervals for the presented mean signals of 125 films for each data point.

the dating of archaeological and geological materials,[5,6] reconstruction of radiation doses following a nuclear accident,[7,8] and space dosimetry.[9] For the megavoltage energy range, the mass energy absorption coefficients and mass stopping powers of carbon-doped aluminum oxide (Al_2O_3:C) are similar to those of water.[10] For these reasons, we have initiated studies on film dosimetry in radiotherapy, based on OSL of Al_2O_3:C. The studies include assessment of the film response (acquired OSL signal/delivered dose) dependence on delivered dose (linearity), dose rate, beam energy (photons and electrons), field size and depth. OSL films have also been compared with conventional x-ray and GafChromic films.

II. METHODS AND MATERIALS

A. Applied OSL films and readout

The OSL films used in this study were provided by Landauer Inc. (Glenwood, USA). They consist of a polystyrene sheet with a top layer of single crystals of carbon-doped aluminium oxide (Al_2O_3:C) ground into a powder, and mixed with a polyester base. The applied films had a diameter of 7.25 mm, and a total thickness of 0.3 mm. They were all packed in a black paper envelope to prevent exposure to environmental light. After irradiation, the films were sent to Landauer Inc. for readout; information on delivered doses was not provided. At Landauer the films were read out with light emitting diodes at 532 nm (green), using sufficiently low intensities for avoiding quenching effects. Each shipment of dosimeters included at least three control dosimeters that were not irradiated in the experiments. The mean control value (typically 60 μGy) was subtracted from the raw dose values. Generally, the time between irradiation and readout by Landauer Inc. was around 14 days. The measurements/readouts were done in eight sessions in a period of 12 months, using a total of 787 OSL films.

B. Measurement phantom, linear accelerators, and beam energies

All measurements were performed in a 41 cm × 41 cm × 38 cm polystyrene phantom made of slabs (0.5, 1 and 2 cm thick). One of the 2-cm-thick slabs had a hole to insert an NE 2571 ionization chamber for dose measurements (see below). The beam axis was always normal to the slabs, and so normal to the film. The source to surface distance was always 100 cm. Apart from the measurements described in Sec. II D, films were always positioned on axis.

TABLE I. Inter-film variations in OSL response for a fixed dose of 200 cGy observed in six measurement sessions.

Session date (No. films)	Signal spread (%, 1 SD)
2nd March '05 (8)	1.4
8th June '05 (53)	1.0
11th July '05 (17)	1.4
23rd August '05 (61)	2.2
19th December '05 (74)	3.2
21st February '06 (15)	1.5

Irradiations were performed with three different linear accelerators:

- Varian Clinac 4 (4 MV photon beam)
- Siemens MD-2 (10 MV photon beam)
- Varian Clinac 2300 C/D (6 and 18 MV photon beams, and 6, 9, 12, 15, 18, and 21 MeV electron beams)

For the 6 MV photon beam, field size and measurement depth dependence of the OSL response was investigated. Beam energy/quality dependence was studied by comparing responses at depths of maximum dose for all mentioned photon and electron beams.

C. Dose assessment

To establish the response of an OSL dosimeter, the OSL signal was divided by the phantom dose at the position of the

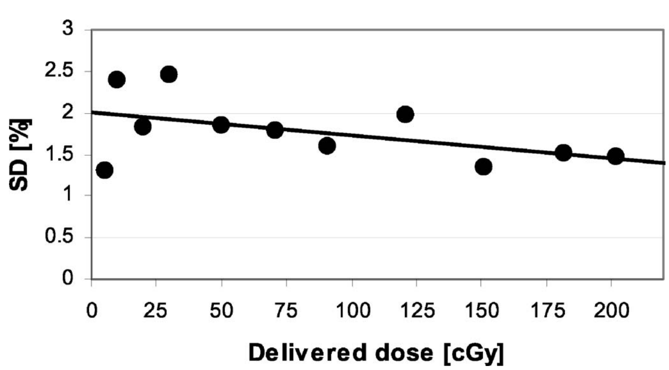

FIG. 2. Inter-film response variation (standard deviation [%]) as a function of delivered dose for the 6 MV photon beam. The straight line was obtained from linear regression through the data points.

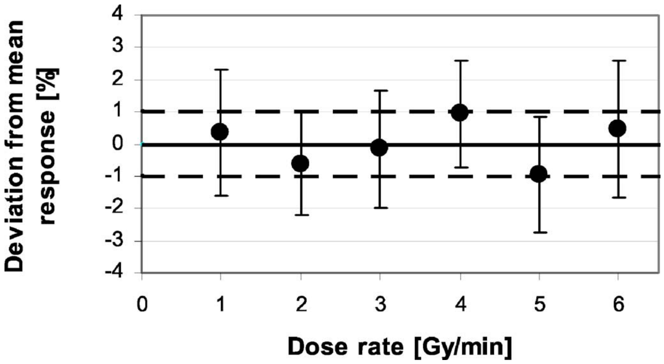

FIG. 3. Dose rate dependence of the OSL signal. The ±1% lines are also indicated. The error bars represent 95% confidence intervals for the presented mean values.

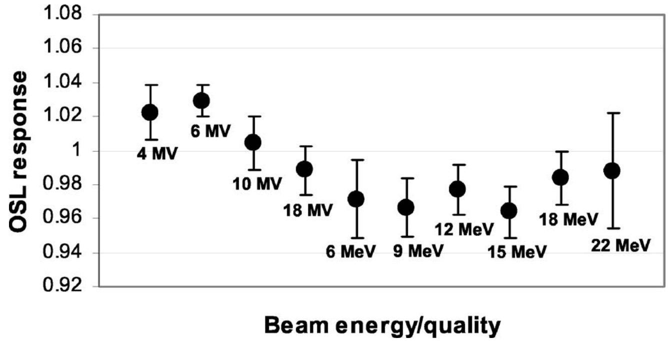

FIG. 5. Beam quality dependence of the OSL signal, derived from measurements with various photon and electron beam energies. The error bars represent 95% confidence intervals for the presented mean values.

film. Assessment of these doses was based on measurements performed with an ionization chamber (Sec. II B).

To determine the response dependence on measurement depth and field size (6 MV), prior to the start with film irradiations, sets of phantom percent depth dose (PDD) curves and output factors were measured for the fields involved in the experiments. The dose measurements were obtained for nominal depths of 1.5, 5, 10, 20, and 35 cm. For construction of PDDs, the effective point of measurement for ionization chamber measurements at depths of 5 cm or more was considered 2 mm above the chamber center.[11,12] For each field, the PDD points for depths ≥ 5 cm were plotted using a logarithmic scale for the dose, and a third order polynomial was fit through the data points. Deviations between measured percent doses and fitted values were always within 0.4% (1 SD). The fitted curves were used to determine PDD values at the depths of film irradiation (in between slabs). On days with film measurements, the absolute dose was measured for the 10×10 cm^2 field at the depth of maximum dose. With the a priori established fitted PDD curves and output factors, and the daily measured absolute dose in reference conditions, absolute doses could be determined for all irradiated films.

The beam energy/quality dependence of the OSL response was studied using measurements at the depth of maximum dose of all involved beams. Each measurement day, the ionization chamber was used to determine the absolute dose for all beams.

During all sessions with film measurements, ionization chamber measurements in reference conditions were performed at the start of the session, and repeated several times to verify constancy of the linac. Observed linac stability was always within 0.1%.

D. Field size and depth dependence of the OSL response (6 MV)

To establish the field size and depth dependence of the OSL response, films were irradiated with fields of 4×4, 10×10, and 30×30 cm^2, and depths of 1.5, 5, 10, 20, and 35 cm. Prior to a measurement session, for each field size/depth combination, the (integer) number of monitor units (MU) was determined such that the delivered dose would be as close as possible to 200 cGy, using the established phantom PPD-curves (see above), and assuming a linac output for reference conditions of 1.00 cGy/MU. Films were then irradiated with these MUs. As explained in Sec. II C, for the response analyses, the actually delivered doses to the films were determined afterwards, using the actual linac output during the measurement session.

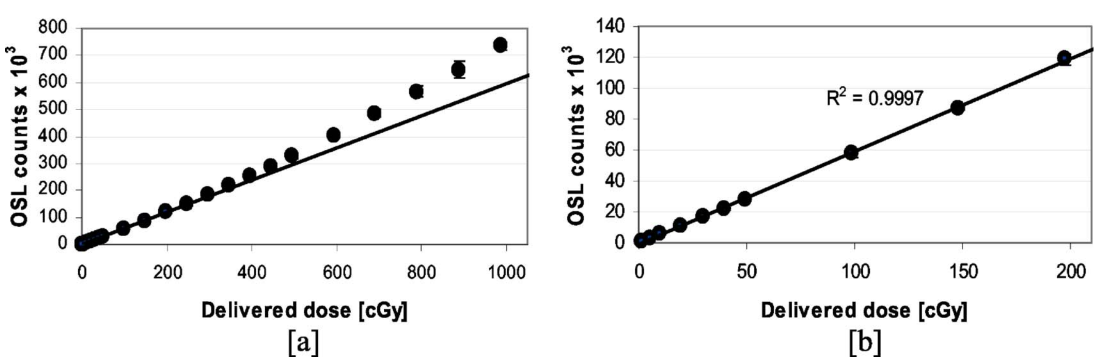

FIG. 4. OSL signal as a function of delivered dose. [a] The straight line is a fit through the data points from 0 to 200 cGy. The error bars represent 95% confidence intervals for the presented mean signals of three films for each data point. The right graph [b] is a blow-up for the range 0–200 cGy.

TABLE II. Relative OSL film response (counts/delivered dose) normalized to the average response over all depths and field sizes. The errors are calculated 95% confidence intervals.

Depth (cm)	Field (4×4)	Field (10×10)	Field (30×30)
1.5	1.000±0.004	0.988±0.008	1.024±0.011
5	0.986±0.012	0.994±0.058	1.017±0.021
10	0.976±0.014	0.992±0.035	1.018±0.014
20	0.984±0.015	1.018±0.027	1.023±0.022
35	0.977±0.016	1.006±0.030	0.997±0.003

E. OSL out-of-field response compared with GafChromic and radiographic films

Out-of-field measurements were performed as a severe test on response dependence on low energy photons. The deviation of the dose response outside the radiation field from the response at the center of the field was evaluated for OSL films, EBT GafChromic films,[13,14] and radiographic films (KODAK X-Omat V). All films were irradiated in a $20\times 20\ \mathrm{cm}^2$ field at 20 cm depth, using 6 or 18 MV photon beams. The off-axis measurements were performed 5 cm from the beam edge. Actually delivered on-axis and off-axis doses were determined from ionization chamber measurements. On-axis films were irradiated with doses in the range 20 to 90 cGy. In the off-axis position, all films received a dose of 50 cGy.

GafChromic and radiographic films were digitized with an Epson scanner following exactly the same procedure. Four scans were performed in order to remove scanner noise by subsequent averaging of the scanned images.[15]

For each film type, the on-axis data were plotted in a graph showing the film signal along the x axis, and dose along the y axis. Third degree polynomials (for GafChromic and radiographic films) and linear (for OSL films) were fit through the data points. The fitted curves were used to derive for each film type the required on-axis dose yielding the same film signal as the applied 50 cGy off-axis dose.

III. RESULTS AND DISCUSSION

A. Fading of OSL signals

In a single measurement session, 125 OSL films were irradiated to a dose of 200 cGy, using fixed conditions. The films were then sent to Landauer Inc. for readout during three subsequent weeks—three times a week (on Monday,

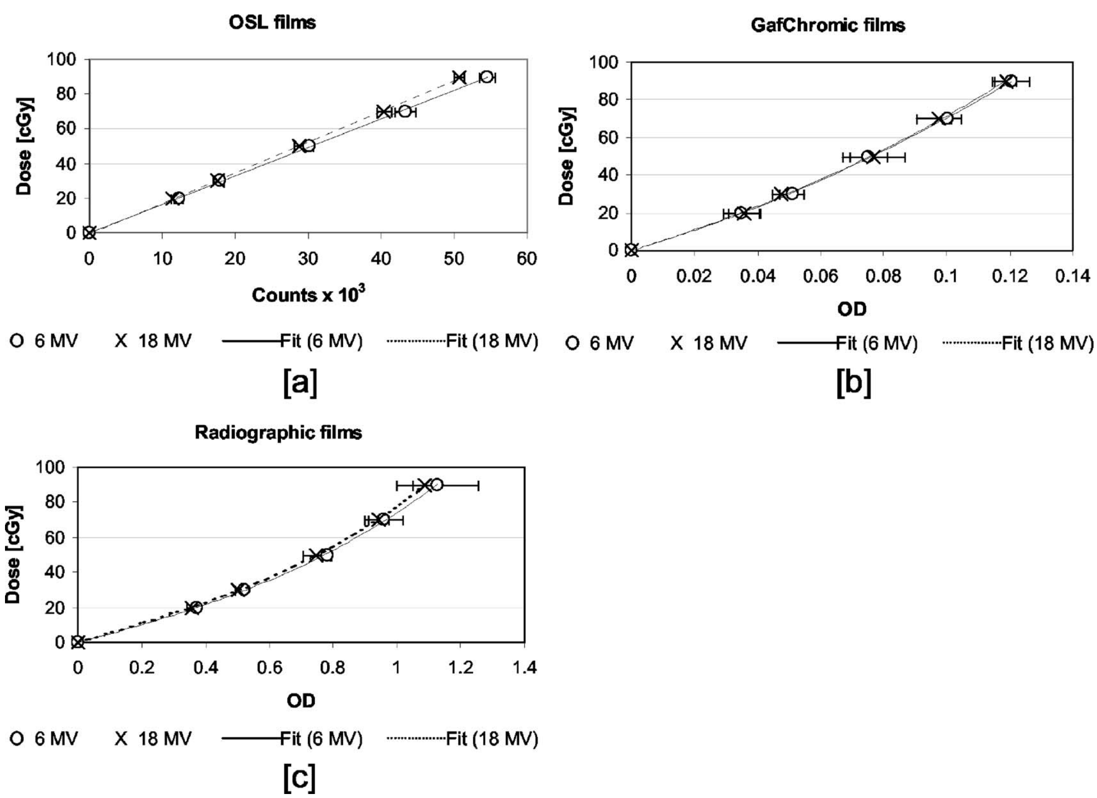

FIG. 6. On-axis dose response curves for OSL [a], GafChromic [b], and radiographic [c] films. All films were irradiated in a $20\times 20\ \mathrm{cm}^2$ field, at a depth of 20 cm. The curves are linear (OSL) and third order polynomial (GafChromic and radiographic) fits.

TABLE III. Film response differences between irradiations outside the high dose area, at 5 cm from the beam edge, and on-axis irradiations in a 20×20 cm^2 field at 20 cm depth.

	6 MV	18 MV
OSL	15.5% (4.9% SD)	20.2% (10.8% SD)
GafChromic	−4.2% (7% SD)	1% (9.8% SD)
Radiographic	47.2% (4.9% SD)	20.7% (2.2% SD)

Wednesday and Friday)—to investigate fading of the OSL signal. Figure 1 shows for each of the ten days with repeat readings the mean deviation from the first day reading. Because of logistical issues, the first reading of the OSL films was performed 17 days after irradiation. Therefore, the behavior of the OSL signal in the first days after irradiation is not known. In the three week period, fading was below 1.8%. The low fading of the OSL signal is in agreement with findings of Bøtter-Jensen *et al.*[4]

B. Inter-film response variation

For absolute dosimetry, OSL films irradiated with the same dose should ideally yield exactly the same OSL reading. Table I shows observed inter-film variations in OSL response for a fixed dose of 200 cGy for six measurement sessions. The response variations are in the range 1%–3.2% (1 SD), depending on the measurement day. Apparently, the real inter-film response variation can be as low as 1% (1 SD). It is unknown whether the observed larger spreads are related to truly higher sensitivity variations among the films, or due to variations in the film processing equipment and procedures. A test was also performed to investigate the inter-film response as a function of delivered dose. In a single session, 125 OSL dosimeters were exposed to doses ranging from 5 cGy up to 202 cGy; all other conditions were constant. For each delivered dose, 11 OSL films (15 for 202 cGy) were exposed. The results are presented in Fig. 2. On average, the spread in readings for doses below 30 cGy is larger than for the higher doses. However, the observed spread for 5 cGy is lower than for 200 cGy. Linear regression through the data points results in a decrease in SD of 0.3%/100 cGy ($p=0.1$).

C. Dose rate dependence of the OSL response

Dose rate dependence was assessed by varying the MU/min setting of the linac, effectively changing the pulse rate and keeping the dose per pulse fixed. The effect of dose rate on the response of OSL films was tested in the range 1 Gy min^{-1} to 6 Gy min^{-1}. For each dose rate, ten OSL samples were exposed to a fixed dose of 2 Gy in the polystyrene slab phantom at d_{max}, using the 6 MV photon beam. It was found that the OSL dosimeter is dose-rate independent. The results are presented in Fig. 3, where the deviations from the mean OSL response for all films remain within 1%.

D. OSL signal versus delivered dose (linearity)

Dependence of the OSL signal on delivered dose was assessed by exposing 63 OSL dosimeters to doses from 1 cGy up to 10 Gy at d_{max} in the polystyrene slab phantom. The results reported in Fig. 4 show that the OSL response is linear for doses lower than 200 cGy. For higher dose values an increased OSL response is observed (supra-linearity). These results agree with data published by Yukihara *et al.*[16,17] They studied the dose response of $Al_2O_3:C$ to beta radiation in the range from about 0.7–1000 Gy, and observed that the OSL dose response shows a linear-supralinear-saturation behavior, with a decrease in the response for doses higher than those required for saturation (> about 80 Gy). The OSL response was linear for doses from 0.7 Gy to about 2 Gy and a supralinear region, accompanied by an increase in sensitivity, was observed before the signal saturation. The dose response behavior and sensitivity changes are similar to those observed in TL of $Al_2O_3:C$.[18]

E. Beam quality dependence of the OSL response

Beam quality dependence of the OSL response was tested using 16 OSL films for 4 and 10 MV, 30 for 6 MV and 23 for 18 MV photon beams. For each electron energy seven films were irradiated. All OSL films used for this experiment were exposed to 200 cGy. Figure 5 shows that there is a significant difference between the mean photon and electron beam responses, equal to 3.7% (95% confidence interval: 2.7%–4.7%). In between the photon beam energies there are also response differences, e.g., 4.1% (95% confidence interval: 2.4%–5.8%) between the 6 and 18 MV beams.

F. Field size and depth dependence of the OSL response

Forty nine OSL films were irradiated on axis with the 6 MV photon beam, using three different field sizes and five depths, as described in Sec. II B. A fixed dose of 2 Gy was delivered. Table II shows OSL responses (counts/delivered dose) relative to the overall mean response for all fields and depths. Observed deviations are within ±2.5%.

G. OSL response outside the radiation field

The on-axis measurements are presented in Figs. 6(a) (OSL), 6(b) (GafChromic), and 6(c) (radiographic). For each on-axis dose and beam energy, three GafChromic films, three Kodak films, and eight OSL films were irradiated. The observed response linearity for OSL [Fig. 6(a)] is in agreement with the data presented in Fig. 4. The difference between the 6 and 18 MV OSL response in Fig. 6(a) is consistent with Fig. 5. For the off-axis measurements, 20 OSL films, three GafChromic films, and three Kodak films were used per energy. Table III shows for each of the two beams and three film types the dose increase compared to 50 cGy, that would be needed in an *on*-axis experiment to obtain the observed *off*-axis film signal.

IV. CONCLUSIONS

In this paper, basic characteristics of OSL in irradiated Al_2O_3:C films for dosimetry in therapeutic photon and electron beams were investigated. Observed response dependencies on dose rate, beam quality, field size, and depth were negligible or small. For 18 MV the sensitivity of OSL is lower than for 6 MV (4%), and equal to the response in the electron beams. This may be related to the relatively high electron energies present in the 18 MV beam, compared to 6 MV. Observed field size and depth dependencies are within 1–2%, making OSL a good candidate for relative dosimetry. To our knowledge, extensive field size and depth dependence measurements have not yet been published for radiochromic and conventional films. The inter-film response variation for films irradiated with the same dose varied from 1% to 3.2% (1 SD), depending on the measurement day. Whether this is a problem for 2D relative dosimetry is unknown, and will be dependent on the exact origin of the observed variation in inter-film response. Over a period of three weeks, fading of the OSL signal was limited to 1.8%. A significant over response was observed outside the radiation field at 5 cm from the field edge, probably related to the presence of a large amount of low-energy scattered photons. In contrast to GafChromic and radiographic films, the response of the Al_2O_3:C films is linear in the clinically relevant dose range 1–200 cGy. In the current study only point measurements were performed. Further research with a two-dimensional reader is needed to fully explore the potential of OSL in irradiated Al_2O_3:C films for radiotherapy dosimetry.

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