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Sensitivity and stability of optically stimulated luminescence dosimeters with filled deep electron/hole traps under pre-irradiation and bleaching conditions

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ABSTRACT

Purpose: We aimed to evaluate the characteristics of optically stimulated luminescence dosimeters (OSLDs) with fully filled deep electron/hole traps, and determine the optimal bleaching conditions for these OSLDs to minimize the changes in dose sensitivity or linearity according to the accumulated dose.
Methods: InLight nanoDots were used as OSLDs. The OSLDs were first pre-irradiated at a dose greater than 5 kGy to fill the deep electron and hole traps, and then bleached ($OSLD_{full}$). $OSLD_{full}$ characteristics were investigated in terms of the full bleaching, fading, regeneration of luminescence, dose linearity, and dose sensitivity with various bleaching conditions. For comparison, OSLDs with un-filled deep electron/-hole traps ($OSLD_{empty}$) were investigated in the same manner.
Results: The fading for $OSLD_{full}$ exhibited stable signals after 10 min, for 1 and 10 Gy. The mean supra-linear index values for $OSLD_{full}$ were 1.001 ± 0.001 for doses from 2 to 10 Gy. Small variations in dose sensitivity were obtained for $OSLD_{full}$ within standard deviations of 0.85% and 0.71%, whereas those of $OSLD_{empty}$ decreased by 2.3% and 4.2% per 10 Gy for unfiltered and filtered bleaching devices, respectively.
Conclusions: Under the bleaching conditions determined in this study, clinical dosimetry with $OSLD_{full}$ is highly stable, minimizing the changes in dose sensitivity or linearity for the clinical dose.

1. Introduction

The use of anion-deficient sapphire doped with carbon (Al_2O_3:C) to obtain optically stimulated luminescence (OSL) is known to have advantages for dosimetry, such as good reproducibility, low energy dependency, and low angular dependency compared to LiF thermoluminescence (TL) dosimetry for energies above MeV [1–5]. Therefore, OSL dosimeters (OSLDs) are widely used for not only *in vivo* dosimetry for cancer patients in the field of radiation therapy, but also personal radiation monitoring in the field of radiation protection [6–8]. Beyond *in vivo* dosimetry and monitoring, OSLDs are also an important tool for auditing and research in the field of radiation therapy [9–11].

Several studies have explained the OSL mechanism using the energy-band model [3,12–14]. When OSLDs are irradiated, free electrons and holes are first generated, and they subsequently separate. The free electrons can potentially be captured by large numbers of shallow, dosimetric, or deep electron traps, depending on the energy band levels [3]. Further, the holes can be captured in deep hole traps and at luminescence centers. Electrons captured by shallow electron traps are released at room temperature within a few minutes, whereas electrons captured by dosimetric electron traps can be held at room temperature for more than 100 days. In addition, electrons are released from dosimetric electron traps when OSL is generated via visible-light stimulation (at wavelengths of 390–780 nm) or at 190 °C temperature [12]. For deep electron traps, delocalization conditions have been reported to involve a temperature of 900 °C and ultraviolet irradiation [12,14,15]. Furthermore, Umisedo et al. have previously demonstrated that wavelengths less than 495 nm force electrons in deep

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electron traps to move to dosimetric electron traps, which may affect the overall luminescence [16]. In OSLDs, electrons released from dosimetric electron traps recombine with holes at the luminescence center, emitting light with peaks centered at 410–420 nm; this light is associated with the absolute dose on the OSLD and is used as a signal for dose determination [8,17]. On the other hand, the recombination of released electrons and holes in deep hole traps leads to heat emission, and hence cannot be used as a signal for dose determination. Deep hole traps compete with luminescent centers for released electrons and, therefore, reduce the overall luminescence.

Omotayo et al. have reported that the signals in OSLDs are primarily affected by the bleaching time, bleaching source wavelength spectrum, stimulation wavelength, and accumulated dose [15]. By using the OSL energy-band model, it has been shown that competition between luminescence centers and deep hole traps, as well as between dosimetric and deep electron traps, causes variation in the OSLD dose linearity and dose sensitivity with accumulated dose [3,12]. For doses greater than 3 Gy, the OSL signal-to-dose (*S*/*D*) ratio trend exhibits a supra-linear curvature because a high dose leads to the filling of the deep electron traps; consequently, dosimetric electron traps are more likely to be filled, causing the gradient of the OSL *S*/*D* curve to increase [18,19]. In contrast to these results, other study has shown that supra-linearity was observable at a dose less than 1 Gy [12]. In various studies, the dose sensitivity has exhibited different trends in response to the accumulated dose under different conditions of bleaching time and bleaching-device wavelength spectrum [3,12,15,20]. It has been demonstrated that the change in dose sensitivity results from the complexity of the competing mechanisms involving the various free electron and hole traps. Thus, Jursinic has suggested the filling of the deep electron and hole traps to remove the effect of the OSLD supra-linearity [12]. By using the Jursinic's approach, the dose linearity could be maintained through the pre-irradiation of OSLDs with dose values greater than 1 kGy.

Despite the previous research on OSLDs ($OSLD_{full}$, which are OSLDs with deep electron/hole traps fully filled by pre-irradiation with dose values greater than 1 kGy), uncertainties associated with dose sensitivity still hinder the clinical use of OSLDs [7,12,21]. Two factors affecting the stable use of OSLDs are the bleaching conditions and the competition discussed in terms of the energy-band model above. In general, the dose sensitivities of $OSLD_{full}$ can be changed without consideration of the bleaching condition because of the competition between the optically released electrons and deep hole traps. Therefore, it is of interest to determine whether the $OSLD_{full}$ sensitivity stabilizes with respect to the accumulated dose as a result of the full filling of the free electrons and holes in the deep electron/hole traps; similarly, investigations of the optimal bleaching sources and times for such devices are also important.

The present study aimed to evaluate the characteristics of $OSLD_{full}$ and to determine the optimal bleaching conditions for reducing their dose measurement uncertainty. In addition, the clinical use of $OSLD_{full}$ with low variation in dose sensitivity or linearity was investigated.

2. Materials and methods

2.1. OSL dosimetry system

The OSL dosimeter used in the present study was an InLight nanoDot device (Landauer, Inc., Glenwood, IL), which was composed of Al_2O_3:C in the form of a disk of 5 mm diameter and 0.2 mm thickness within a 10 × 10 × 2 mm^3 lightproof plastic case.

The OSLDs were read with an InLight MicroStar reader (Landauer, Inc., Glenwood, IL) operated in the continuous-wave (CW) mode with an illumination read period of 1 s using weak-stimulation light-emitting diode (LED) modes. InLight MicroStar reader uses the green stimulation LED having a median wavelength of 530 nm for weak-stimulation of OSLDs. This wavelength forces electrons to be moved from dosimetric electron traps and doesn't have a great influence on the sensitivity change of OSLDs. Before readout, measurements to check the stability of the reader were performed 3–5 times using three of the reader modes: "DRK," "CAL," and "LED." These measurements were conducted by assessing the photomultiplier tube (PMT) signal in response to stimuli. Note that "DRK" represents the PMT response without stimulus, which is an indicator of the electric noise or dark current. "CAL" is the PMT response to C-14 ($T_{1/2}$ = 5730 years) encapsulated in a powdered phosphor. Finally, "LED" is the PMT response to the LED source in the reader used to stimulate OSLDs during readout; this is a reading of the counts recorded when the LED is activated [15]. After these standard measurements, each OSLD signal was recorded an average value of five readings, yielding a coefficient of variation (CV) < 0.9%.

After the OSLDs had been read, a bleaching device (Hanil Nuclear, Inc., Gyeonggi-do, Korea) was used for bleaching. 36 LED chips (ATI-5730PWHB-L, ATI LED Inc., Jiangsu, China) with 15-W 6100-K color temperature (white light) measuring 38.0 × 3.4 cm^2 were used as a bleaching source in the OSL dosimetry system. The bleaching source had a wide wavelength in the 400–750-nm range, with two peaks at approximately 450 (blue) and 550 nm (yellow). A 520 nm long-pass filter (Edmund Optics, Inc., Barrington, NJ) was applied to block LED light components with wavelengths less than 520 nm. This filter was used selectively for the experiment including the dose sensitivity, linearity and finding optimal bleaching conditions. The wavelength spectra of the bleaching source for unfiltered and filtered light were measured 2–3 times at several points (anterior, posterior, middle, left, and right sections in bleaching source) using a USB4000 spectrometer (Ocean Optics, Inc., Dunedin, FL) and there has been no difference between those spectra. Then, we have chosen the wavelengths of bleaching source measured as Fig. 1.

2.2. Pre-irradiation and experimental setup

The experimental sample consisted of 60 OSLDs that were pre-irradiated with an accumulated dose of 5 kGy by using a Co-60 gamma-ray source. The Co-60 source (MDS Nordion, Ottawa, ON,

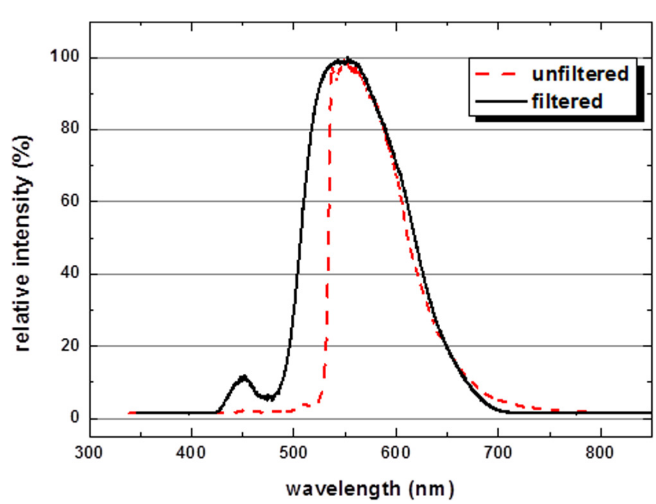

Fig. 1. Wavelength spectra of unfiltered and filtered bleaching devices. A 520 nm long-pass filter was used to block the LED light components with wavelengths less than 520 nm.