Technical note

Temporal modelling of beryllium oxide ceramics' real-time OSL for dosimetry with a superficial 140 kVp X-ray beam

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ABSTRACT

A new analysis method for the rtOSL of BeO ceramics is presented, using temporal curve fitting of an expected rtOSL signal to measured rtOSL signals. The presented technique does not require heavy signal averaging to determine the OSL bleaching correction associated with the Δ rtOSL method, reducing uncertainties in the post-correction rtOSL. The corrected rtOSL signal was demonstrated to be linear with dose, and dose-rate independent. The presented technique is expected to be applicable for many other dosimeters capable of the rtOSL technique. The presented technique achieved relative uncertainties in the corrected rtOSL between 3.4% and 6.5%. The initial measurements are promising, but uncertainties are required to be further improved upon before the technique can be used clinically.

1. Introduction

Fibre optic dosimeters (FODs) using beryllium oxide (BeO) ceramics as their sensitive volume material have been shown to be promising detectors for relative dosimetry measurements with many X-ray modalities [1–7]. BeO ceramic materials possess energy independent dose-response by Bragg-Gray theory across a wide range of therapeutic X-ray energies [4], while BeO volumes can be manufactured to have millimetric volumes and achieve high spatial resolutions [7].

As with many FODs, non-negligible stem signals are generated when the BeO coupled FOD's optical fibre is irradiated. Many stem correction methods for FODs are designed for use with scintillator coupled FODs, and have drawbacks when applying them with BeO coupled FODs. Spectral discrimination methods utilise the difference between a luminescent dosimeters' emission spectra and the stem emission spectra [8,9]. Given BeO's peak emission wavelength of 370 nm [5] and the continuous output spectra of Cerenkov radiation [10], a spectral discrimination methods' accuracy may be degraded for use with BeO coupled FODs [5]. Air-core fibre methods avoid the generation of Cerenkov radiation in optical fibre cores [11], however, air-core fibres have

high signal attenuation coefficients that make them undesirable where long fibre lengths are required. Temporal analysis methods require pulsed radiation sources with relatively short pulse widths and relatively long duty cycles [12–14], however BeO ceramics have a short luminescence lifetime.

Another stem correction approach for OSL dosimeters, real-time optically stimulated luminescence (rtOSL), performs real-time measurements of optically stimulated luminescence (OSL) while a pulsed optical stimulus is applied [15–20]. At times where the laser stimulus is off, only RL and stem signals are measured; at times where the laser stimulus is on, the RL, stem and OSL signals are measured. The desired rtOSL signal is achieved by taking the difference of signals measured when the laser is on and off, respectively.

In previously established rtOSL methods, a post-measurement correction technique (referred to as Δ rtOSL) was required to correct for incomplete bleaching of the OSL traps during the OSL dosimeter irradiation. This correction technique used significant signal averaging to investigate the change in rtOSL output as a function of time, however the heavy signal averaging induced significant uncertainties. The Δ rtOSL technique was used with a BeO coupled FOD for superficial X-

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ray dosimetry in previous work [7]. The same raw data (i.e. the measured, uncorrected optical signals) from Santos et al. [7] was reused for this work; in this work, a novel signal analysis technique is presented that reduces the uncertainty in BeO's corrected rtOSL response, and removes the requirement for post-measurement signal averaging during the Δ rtOSL technique. This reduction in uncertainty is achieved through kinetic modelling and computational curve fitting as opposed to strong signal averaging.

2. Materials and methods

The BeO fibre-optic dosimeter consisted of a cylindrical volume of BeO (Thermalox 995, Materion, USA) optically coupled to two silica optical fibres. The BeO cylinder had a diameter of 1 mm and a length of 1 mm. The two optical fibres were 20 m long and had inner core diameters of 200 μ m (FG200UEA, Thorlabs, USA) and 400 μ m (FP400URT, Thorlabs, USA), respectively. The 200 μ m optical fibre was used to transport stimulation light from a 40 mW blue (450 nm) laser diode (Z-laser, Germany) to the BeO cylinder. The 400 μ m optical fibre was used to collect the BeO luminescence signal and transport the rt-OSL signal to a photomultiplier tube (H7360-01, Hamamatsu, Japan). The two optical fibres were positioned abreast and parallel (shown in Fig. 1), being coupled to the same circular face of the BeO cylinder to minimise the optical stimulation light measurable by the photomultiplier tube (without using a beam-splitter).

A USB-6341 (National Instruments Inc., USA) data acquisition card (DAQ) was used to simultaneously control the laser diode output and record the photomultiplier tube (PMT) output. The laser diode emitted a 2 Hz square wave with a 50% duty cycle, and the PMT output was recorded at a sampling rate of 1 kHz. At times when the PMT output was recorded while the laser was off, the RL and stem signals were measured; at times when the PMT output was recorded while the laser was on, the RL, stem and rtOSL signals were measured. The rtOSL signal was extrapolated as the difference between PMT outputs while the laser was on and off, as shown in Fig. 2.

The BeO-FOD was irradiated using a Gulmay D3150 (Gulmay Medical Ltd., UK) superficial X-ray unit. The superficial X-ray unit produced a 140 kVp X-ray beam with 8 mm aluminium half value layer and a 5 cm diameter. The BeO-FOD was positioned at the proximal surface of a 8 cm thick block of solid water phantom (Gammex RMI, Middleton, U.S.A.) with source-surface distances of 15 cm, 25 cm, 35 cm, 45 cm and 55 cm; these source-surface distances have corresponding nominal dose-rates (at the surface in water) of 3.88 Gy/min, 1.42 Gy/min, 0.72 Gy/min, 0.44 Gy/min and 0.29 Gy/min, respectively, in accordance with the IPMB code of practice [21]. For each rtOSL measurement, the PMT outputs were recorded as the BeO-FOD was irradiated for 5 min, then bleached for 5 min. From the 5 rtOSL measurements, the corrected rtOSL linearity with respect to dose and corrected rtOSL dependence on dose-

Fig. 2. In the plots, Total corresponds to the laser on signal (blue), stem corresponds to the laser off signal (black) and rtOSL corresponds to the difference between the laser on and laser off signal (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rate were determined.

2.1. Temporal signal modelling

In recent work with plastic scintillation dosimeters, temporal kinetic modelling was applied to derive the expected scintillation, $S(t)$, in response to some time dependent dose-rate $\dot{D}(t)$ [22]. It was found that the expected scintillation was proportional to the mathematical convolution of the dose-rate as a function of time, $\dot{D}(t)$, and an exponential rise and decay that is characteristic of the plastic scintillator [22]. Similarly, the measured rtOSL signal is dependent on a time dependent dose-rate, $\dot{D}(t)$, hence the same technique is applicable for rtOSL. The expected rtOSL in response to some time dependent dose-rate, $\dot{D}(t)$, is proportional to the convolution of $\dot{D}(t)$, and some exponential rise and decay characteristic of BeO's rtOSL. From classical kinetic modelling, BeO's characteristic OSL is given by [23]:

$$OSL(t) \propto a \cdot e^{-\frac{t}{\tau_1}} + (1-a) \cdot e^{-\frac{t}{\tau_2}} \quad (1)$$

where a is a constant with value between 0 and 1, $g(t)$ is the intensity of the optical stimulus as a function of time, and τ_1 and τ_2 are exponential decay time constants, respectively. Prior to the rtOSL measurements being made in this work, the effective values for a , τ_1 and τ_2 were unknown. In the presented work, $g(t)$ was a square wave with frequency of 2 Hz, bounded between relative intensities of 0 and 1. The pulsed stimulus can be approximated as a continuous wave stimulus with relative intensity equal to 1/2. The expected rtOSL as a function of time, $I_{rtOSL}(t)$, is given by:

$$I_{rtOSL}(t) \propto \dot{D}(t) * \left(a \cdot e^{-\frac{t}{\tau_1}} + (1-a) \cdot e^{-\frac{t}{\tau_2}} \right) \quad (2)$$

The time dependent dose-rate, $\dot{D}(t)$, is required to be measured simultaneously with the rtOSL signal. BeO's radio-luminescence has an exponential decay constant in the order of tens of microseconds [24]. Similarly, the stem signal generated by the pure silica optical fibre has an exponential decay constant in the order of tens of microseconds [25]. The stem + RL signals were too fast to be temporally resolved by the DAQ, hence the measured stem + RL signal is proportional to $\dot{D}(t)$.

To determine the values of a , τ_1 and τ_2 , sets of measured rtOSL and

Fig. 1. 3D model of the measurement setup with a cutaway in the photon beam to show the rtOSL dosimeter (not to scale). Close up of the BeO ceramic volume and optical fibres is shown in the top right corner.

stem + RL signals were measured so that the values of a , τ_1 and τ_2 could be determined iteratively using random number sampling. For each value of a , τ_1 and τ_2 , the resultant $I_{\text{rtOSL}}(t)$ signal was used in a gradient descent algorithm to fit the estimate, $Y = b \cdot I_{\text{rtOSL}}(t) + c$ to measured rtOSL signals, T . In the gradient descent algorithm, the cost function was the sum of the squared errors (SSE) between Y and T , and the stopping criteria required 5 consecutive iterations where the newest iterations' SSE was greater than the minimum SSE recorded. From linear regression, the standard deviation in the fitted rtOSL signal is given by the root mean squared error between Y and T .

The optimal values of a , τ_1 and τ_2 were found when the global sum of all signal's SSEs was minimised (referred to as a_{opt} , $\tau_{1\text{opt}}$ and $\tau_{2\text{opt}}$). The uncertainty in a_{opt} , $\tau_{1\text{opt}}$ and $\tau_{2\text{opt}}$ was determined by optimising a , τ_1 and τ_2 for each individual signal (let resultant parameters for the i^{th} signal be referred to as a_i , τ_{1i} and τ_{2i}), and calculating the standard deviation between the group of a_i , τ_{1i} and τ_{2i} , while using a_{opt} , $\tau_{1\text{opt}}$ and $\tau_{2\text{opt}}$ as the mean value.

2.2. OSL decay correction

BeO's accumulated rtOSL response is non-linear as a function of absorbed dose [6,7], subject to a decay in rtOSL output as absorbed doses increase. This non-linear response requires correction to linearise the response as a function of dose. In the ΔrtOSL technique, the correction multiplied the rtOSL of the n^{th} pulse by $F(D)^{n-1}$, where $F(D)$ was treated as a constant to correct for the decay in output rtOSL. In previous work with BeO, the ΔrtOSL technique required heavy signal averaging in order to reduce the uncertainty in the corrected rtOSL signal. With the temporal curve fitting approach presented in this work, signal averaging is not required to extrapolate an accumulated rtOSL decay correction. From a first order Taylor series expansion of $e^{F(D) \cdot t} \approx (1 + F(D) \cdot t)$, the pulse by pulse OSL decay correction used in the ΔrtOSL technique is achieved. The fitted rtOSL can be empirically corrected by multiplying the fitted rtOSL, Y by an exponential function with respect to time, $e^{F(D) \cdot t}$. Consequently, the rtOSL decay correction factor, $F(D)$, is related to the rtOSL, $Y(t)$, and the accumulated dose, $D(t)$, by:

$$\ln\left(\frac{D(t)}{Y(t)}\right) = F(D)t + \text{constant} \quad (3)$$

The rtOSL decay correction factor, $F(D)$, was the slope when linear regression was used to fit a trend-line to the natural log of the accumulated dose divided by the rtOSL, and the time axis. The uncertainty in each $F(D)$ was consequently the standard error of the slope during the aforementioned linear regression fitting process. The OSL bleaching correction was applied by multiplying each rtOSL signal, $Y(t)$, by the exponential $e^{F_{\text{Ave}}(D) \cdot t}$, where $F_{\text{Ave}}(D)$ was the average $F(D)$. The uncertainty in $F_{\text{Ave}}(D)$ was calculated by combining the average uncertainty of each $F(D)$ with the standard error of the measured $F(D)$ values.

3. Results

The 5 sets of rtOSL and corresponding stem + RL signals were measured. The optimal values of a_{opt} , $\tau_{1\text{opt}}$ and $\tau_{2\text{opt}}$ were determined to be $a_{\text{opt}} = 0.41 \pm 0.04$, $\tau_{1\text{opt}} = (328 \pm 12)$ s, and $\tau_{2\text{opt}} = (64 \pm 8)$ s. The measured rtOSL signals and the rtOSL fits using a_{opt} , $\tau_{1\text{opt}}$ and $\tau_{2\text{opt}}$ are plotted in Fig. 3. Shaded regions in the Fig. 3 correspond to the 95% confidence interval in the fit rtOSL.

3.1. Accumulated rtOSL-dose correction

The fitted rtOSL (as a function of time) was plotted as a function of the accumulated dose at time t , shown in Fig. 4. The natural log of the accumulated dose divided by the rtOSL was plotted against time, shown in Fig. 5. The expected linearity trend is not observed in the first 30 s of

Fig. 3. Points correspond to measured rtOSL signals (uncorrected), lines correspond to fitted rtOSL signals (uncorrected) and shaded regions correspond to the 95% confidence interval in each fitted rtOSL signal.

Fig. 4. Fitted rtOSL signal plotted as a function of accumulated dose (corresponding to duration of irradiation multiplied by each nominal dose-rate). Fitted signals are only investigated for times where BeO is being irradiated; post-irradiation rtOSL is not investigated.

irradiation; for this reason, the first 30 s of each fit was excluded when fitting the linear trend. From Eq. 3, the rtOSL decay correction $F(D)$ was calculated by fitting a linear trend-line to the natural log of the accumulated dose divided by the rtOSL, and the time axis. The decay correction factors, $F(D)$, and their uncertainties, $\Delta F(D)$ were calculated for each rtOSL signal, presented in Table 1. The relative uncertainties in the 5 fitted $F(D)$ s ranged between 0.3% and 0.6%.

The fitted rtOSL signals were corrected for OSL bleaching by multiplying each rtOSL signal at time t , $Y(t)$, by $e^{F_{\text{Ave}}(D) \cdot t}$, where F_{Ave} was the average of all $F(D)$ calculated. The uncertainty $\Delta F_{\text{Ave}}(D)$, was calculated by combining the average uncertainty of each $\Delta F(D)$ with the standard error of the calculated $F(D)$ values. The decay corrected rtOSL is shown in Fig. 6.

3.2. rtOSL-dose linearity and dose-rate independence

BeO's rtOSL signals were measured at the 5 SSDs. After fitting the expected rtOSL signals to the measured rtOSL signals and correcting the fitted rtOSL signals for OSL bleaching, the maximum value of each

Fig. 5. In (a), $\log(D(t)/Y(t))$ corresponds to $\ln\left(\frac{D(t)}{Y(t)}\right)$ as in Eq. (3). Linear trends are fit to $\left(\frac{D(t)}{Y(t)}\right)$ versus time to determine each rtOSL's $F(D)$.

Table 1

The table presents each signals' $F(D)$, equal to the slope of the linear fit using Eq. 3. $\Delta F(D)$ corresponds to the standard error in each slope that was fit using Eq. 3. $\Delta F(D)/F(D)$ corresponds to the relative uncertainty in each slope.

Dose-rate (Gy/min)	$F(D)$ s^{-1}	$\Delta F(D)$ s^{-1}	$\Delta F(D)/F(D)$ %
3.884	1.7×10^{-3}	4.5×10^{-6}	0.3
1.4169	1.9×10^{-3}	6.5×10^{-6}	0.3
0.7229	1.8×10^{-3}	4.8×10^{-6}	0.3
0.4373	2.0×10^{-3}	8.4×10^{-6}	0.4
0.2928	2.1×10^{-3}	1.2×10^{-5}	0.6
Average	1.9×10^{-3}	5.8×10^{-5}	3.1

Fig. 6. Corrected rtOSL signal plotted as a function of accumulated dose (corresponding to duration of irradiation multiplied by each nominal dose-rate). Corrected signals were only investigated for times where BeO is being irradiated, as in Fig. 4.

corrected signal was taken as BeO's corrected rtOSL response. BeO's corrected rtOSL linearity with respect to dose was quantified by fitting a linear trend-line of $\max(Y) = k \times D$ to the plot of $\max$ rtOSL response, $\max(Y)$ versus the known dose delivered to BeO during each

measurement, D (shown in Fig. 7). The trend-line had an $R^2 = 0.99988$, suggesting that the integral rtOSL dose-response of BeO was linear.

The dose-rate dependence of BeO's rtOSL was investigated by normalising each measured rtOSL signal by the dose-rate during its measurement. The expected rtOSL signal was fit to the dose-rate normalised rtOSL signals, with the fitted and measured signals shown in Fig. 8(a). After correction, BeO's rtOSL response was investigated for its dose-rate dependence by dividing the corrected rtOSL signals in Fig. 7 by the dose-rate at which each signal was measured. The resultant dose-rate normalised rtOSL responses are plotted in Fig. 8(b) (being normalised to the response at 3.884 Gy/min). With the uncertainties taken into account, the fitted rtOSL responses did not show any dose-rate dependences. However, the normalised stem-RL responses in Fig. 8(b) exhibit increasing responses per unit dose-rate as dose-rates decrease; this apparent trend arose as increasing lengths of optical fibre were irradiated as the SSDs increased and dose-rates decreased. From the mismatched trends exhibited by the rtOSL and stem + RL responses in Fig. 8(b), the rtOSL approach completely removed the stem signal from the rtOSL signal. Furthermore, the dose-rate normalised rtOSL signals in Fig. 8(a) and corresponding responses in Fig. 8(b) support that BeO's rtOSL signals are dose-rate independent across the dose-rates tested, as previously reported by Santos et al. [7].

4. Discussion

In this work, after correcting for OSL bleaching, the relative uncertainties in the rtOSL responses varied between 3.4% at 3.884 Gy/min and 6.5% at 0.2928 Gy/min. Of these relative uncertainties, the relative uncertainty in the bleaching correction was a constant 3.2%, and the relative uncertainty in the fitted rtOSL ranged between 1.2% at 3.884 Gy/min, and 6.1% at 0.2928 Gy/min. The relative uncertainties in BeO's dose-response when using the Δ rtOSL technique to correct for the non-linear rtOSL response are not reported in the literature. The Δ rtOSL technique was applied to the same data used in this manuscript [7], and the relative errors were using the Δ rtOSL technique were of the order of tens of percent. The presented curve fitting technique improves upon the accuracy of rtOSL measurements and does not require the signal averaging of the Δ rtOSL technique, achieving reduced uncertainties through curve fitting.

The linear trend expected from Eq. 3 was not observed in Fig. 5. The asymptotic behaviour in the first seconds of Fig. 5 arise due to the non-zero intercepts of the fitted rtOSL. The optimal fits of the expected rtOSL, $Y = b \cdot I_{\text{rtOSL}}(t) + c$, resulted in c values that did not equal zero. Optimal fits resulted in c values of $(-0.13, 0.05, -0.02, 0.04 \text{ and } 0.06) \times 10^4$

Fig. 7. Corrected rtOSL linearity with respect to dose of BeO's corrected rtOSL. In the plot, rtOSL is the corrected rtOSL after 5 min of irradiation, and Dose is the nominal accumulated dose deposited in BeO.

Fig. 8. In (a), the rtOSL signals (uncorrected) were normalised by the nominal dose-rate of during irradiation. Points corresponded to measured rtOSL (normalised by dose-rate), and lines corresponded to fitted rtOSL signals (normalised by dose-rate). In (b), are the bleaching corrected rtOSL responses and stem + RL signals, normalised by the nominal dose-rates during irradiation.

Counts/s for dose-rates of (3.88, 1.42, 0.72, 0.44 and 0.29) Gy/min, respectively. In the plots in Fig. 5, positive c values correlated to $\log(\text{Dose/Responses})$ that approached $-\infty$ as $t \rightarrow 0$, where the negative c values correlated to $\log(\text{Dose/Responses})$ that approached $+\infty$ as $t \rightarrow 0$. The non-zero c values are responsible for the asymptotic behaviour of the plotted $\ln\left(\frac{D(t)}{Y(t)}\right)$ during the first seconds of irradiation in Fig. 5.

The non-linearity in Fig. 5 arises due to the wide distribution of optical sensitive trapping centres in BeO's band structure. With regards to BeO's band structure, there exists optically active (OA) trapping centres (responsible for the majority of OSL emissions), hard to bleach (HB) trapping centres and deep trapping centres in BeO's band structure [26]. Of these trapping centres, the optical stimulus is efficient at emptying OA centres, but inefficient at emptying HB centres and deep centres [26]. During optical stimulation, the filled HB centres and deep centres transfer a fraction of their charges the conduction band, which can relax to OA centres [26]. Consequently, the optical bleaching of BeO's OA trapping centres do not follow first order kinetics (not described by a single exponential function), as is the case for Al_2O_3 [27,28]. The non-linearity in Fig. 5 arises due to the non-first order

kinetics of optical bleaching, leading to increased uncertainties. The plotted $\ln\left(\frac{D(t)}{Y(t)}\right)$ behaves approximately linearly after the first 30 s (corresponding to an approximation of first order kinetics after 30 s of irradiation). As the correction using $e^{F(D)t}$ assumes first-order kinetics and the correction is empirical in nature, the first 30 s of the signal that are observably problematic are excluded when determining $F(D)t$. With errors taken into account, the dose-rate normalised rtOSL signals in Fig. 8(b) remain dose-rate independent, supporting the exclusion of the first 30 s of rtOSL signal when determining $F(D)$.

In Fig. 8(b), the deviations from 100%·min/Gy are systematic in nature. The correction factor $e^{F(D)t}$ slightly overestimates $\ln\left(\frac{D(t)}{Y(t)}\right)$ at a time of 300 s, leading to supralinearity at the maximum accumulated dose in Fig. 6. The resultant deviations of the dose-rate normalised response from 100%·min/Gy in Fig. 8(b) arise due to the overestimation by the empirical correction, with a maximum deviation of 5.5% at 0.2928 Gy/min. The corresponding uncertainties of the dose-rate normalised rtOSL in Fig. 8(b) allow the corrected rtOSL signals to remain dose-rate independent, however the described systematic trend highlights the need for another correction method. A more theoretical approach modelling the optical bleaching is expected to reduce the associated uncertainty in the corrected rtOSL signal, and would eliminate systematic trends in Fig. 8(b).

The presented temporal curve fitting technique is expected to be applicable with many dosimeters capable of the rtOSL technique. The characteristic OSL of a material can be expected to be multi-exponential, with the number of exponential components equal to the number of optically active trap species in the material. The decay constants τ_i are expected to be dependent on the intensity of the laser stimulus [23]. The reported values of τ_1 and τ_2 are therefore expected to vary between set-ups.

In this work, the model was limited to 2 optically active traps. Yukihiro's proposed band structure of BeO allows for many trap species to contribute to OSL [26]. As such characteristic OSL models with 3, 4 and 5 traps were tested. For these 3, 4 and 5 trap models, the optimal parameters were found using the random number sampling approach in Section 2.1; the resulting global sum of SSEs for 3, 4 and 5 traps was greater than the global sum of SSEs for a 2 trap model of characteristic rtOSL. The presented method convolving characteristic OSL with a time dependent dose rate is expected to be applicable to materials whose characteristic OSL can be described by the sum of exponentials.

5. Conclusion

A new analysis method for the rtOSL of BeO was presented, based around temporal curve fitting of an expected rtOSL signal to measured rtOSL signals. The presented technique does not require heavy signal averaging to determine the OSL bleaching correction associated with the ΔrtOSL method, reducing uncertainties in the post-correction rtOSL. The corrected rtOSL signal was demonstrated to be linear with dose, and dose-rate independent. The presented technique is expected to be applicable for many other dosimeters capable of the rtOSL technique. The presented technique achieved relative uncertainties in the corrected rtOSL between 3.4% and 6.5%. The initial measurements are promising, but uncertainties are required to be further improved upon before the technique can be used clinically.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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