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Technical note

Evaluation of a real-time optically stimulated luminescence beryllium oxide (BeO) fibre-coupled dosimetry system with a superficial 140 kVp X-ray beam

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ABSTRACT

The purpose of this study was to investigate the potential of real-time optically stimulated luminescence (rtOSL) measurements of a beryllium oxide (BeO) ceramic fibre-coupled luminescence dosimetry system. By pulsing the stimulation laser during the exposure to ionizing radiation, an rtOSL dose-rate measurement can be obtained which could be stem effect free. A portable rtOSL BeO ceramic fibre-coupled dosimetry system is presented and characterized using a constant dose-rate superficial 140 kVp X-ray beam. The rtOSL was measured for dose-rates between 0.29 and 3.88 Gy/min, controlled by varying the source to surface distance. After correcting for OSL decay during the exposure, a linear dose-rate response of the change in rtOSL (ΔrtOSL) was observed. The ΔrtOSL was also observed to be stem effect free.

1. Introduction

Fibre-coupled luminescence dosimetry systems utilizing beryllium oxide (BeO) ceramics as the probe material have shown some promise in their application to radiotherapy dosimetry [1–4]. The major advantage in the use of BeO ceramics is the potential to be an energy independent dosimetry system due to their closely matched effective atomic number with water [5].

One major issue associated with all fibre-coupled luminescence dosimetry systems is called the stem effect. This is unwanted background light measured when a fibre optic is exposed to ionizing radiation. This can be due to either Cerenkov radiation or luminescence from within the optical fibre core. While various methods have been developed for the correction of stem effect, many of these are not applicable for a BeO ceramic probe [6].

The first approach is the use of a second optical fibre with no scintillator coupled to it, and hence the second optical fibre will only measure the stem effect [7]. This approach requires two photomultiplier tubes and can result in errors if the two optical fibres are not aligned well. Spectral discrimination methods have also been used with scintillators which have an emission spectrum different from the stem effect [8]. Due to the main emission of BeO ceramic around 370 nm, spectral discrimination techniques may be difficult at higher energies where the Cerenkov is dominant [6].

Temporal discrimination methods when the radiation is pulsed have also been applied to scintillators with a long scintillation life time, and more recently using convolutional neural networks [9,10]. These temporal approaches are not useful for continuous radiation sources. The use of air core optical fibres which do not produce any stem effect have been reported [11]. However, air core light guides have a higher optical attenuation of the scintillators emission [12].

Another approach to correct for the stem effect may be the use of real-time optically stimulated luminescence (rtOSL) measurements of the dose-rate. This approach is performed with a pulsed laser during the exposure of the BeO ceramic probe. By subtracting the light measured during the laser pulses, by the light between the laser pulses, it is possible to obtain an rtOSL measurement during exposure to radiation which is stem effect free. This approach has been utilized for Al_2O_3:C and KBr:Eu probe systems [13–18]. However, due to the high effective atomic number of these probe materials, they are observed to have an increased response at low X-ray energies and therefore are not energy independent.

Recently, this rtOSL technique was investigated for a BeO ceramic system [6]. Teichmann et al. observed that the real-time OSL was stem effect free and responded linearly with dose-rate. While this approach has been shown to have promise with Sr-90 sources of dose-rates between 0.3 and 3.6 Gy/hr, the dose-rates examined are quite low when compared to those applicable to radiotherapy radiation beams.

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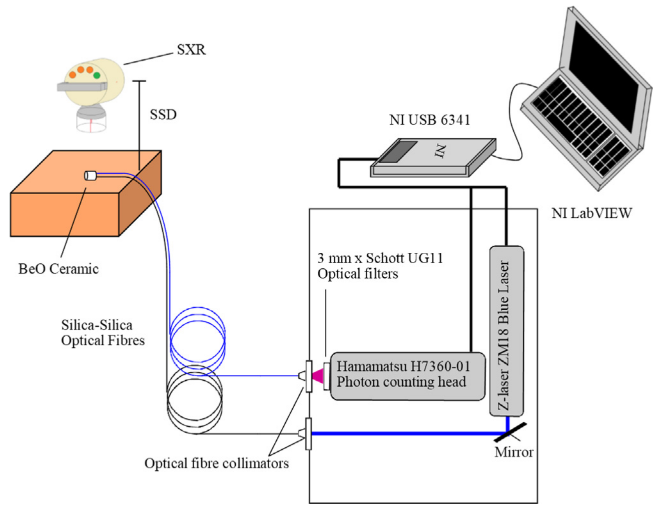

Fig. 1. The rtOSL BeO ceramic dosimetry system, consisting of two silica optical fibres and fibre collimators, a photomultiplier tube and blue laser, controlled using a portable USB DAQ and laptop. The rtOSL BeO dosimeter is placed on the surface of a solid water slab and exposed to a superficial X-ray unit.

Therefore it is important to investigate the response of the real-time OSL in therapeutic conditions. In this study we report on the rtOSL results obtained from a fibre-coupled BeO ceramic dosimetry system, using a constant high dose-rate, therapeutic energy X-ray source.

2. Methods and materials

2.1. Reader system

The dosimetry system used in this study, shown in Fig. 1, consists of a 1 mm diameter BeO ceramic cylinder of 1 mm length (Thermalox 995, Materion, USA), coupled to two silica-silica optical fibres. The two fibres used are side by side, one fibre was used for guiding the luminescence from the BeO ceramic to a photomultiplier tube (PMT), Hamamatsu H7360-01 photon counting head (Hamamatsu, Japan). The second fibre was used to guide the blue stimulation laser light from a 40 mW blue (450 nm) laser diode (Z-laser, Germany). The optical fibres are 20 m in length, with the first having a 400 um diameter core, FP400URT (Thorlabs, USA), while the second has a 200 um diameter core, FG200UEA (Thorlabs, USA). A two fibre approach was used to reduce the stimulation light at the PMT. This way a beamsplitter was not required and hence allowed for the use of less filtration.

The data acquisition card (DAQ), USB-6341 (National Instruments Inc., USA), was reading the PMT at a sampling rate of 1 kHz and continuously pulsing the laser at a rate of 2 Hz with a 50% duty cycle. By pulsing the laser during the exposure of ionizing radiation, rtOSL readings are performed shown in Fig. 2.When the laser is off, the light collected is contributed from the radioluminescence (RL) from the BeO ceramic and the stem effect. When the laser is on the light collected is contributed from the RL, stem and OSL. By subtracting the mean counts measured between the laser pulses from the mean counts measured during the laser pulses, an rtOSL signal can be obtained which is independent of the stem effect. In order to perform this analysis the data acquisition card records the counts measured from the PMT and the state of the laser. Some background laser light is also guided to the PMT within the optical fibre which is also subtracted.

2.2. Superficial X-ray exposure

Measurements were taken with the use of a superficial X-ray unit (SXR), Gulmay D3150 (Gulmay Medical LTD., UK), with an X-ray beam of 140 kVp, 8 mm Al half value layer and 5 cm diameter field size, shown in Fig. 1. An SXR was used because it is a constant dose-rate source of X-rays and the dose-rate can be easily varied. The BeO ceramic dosimetry system was placed on the surface of a solid water slab (8 cm × 40 cm × 40 cm). Five different source to surface distances (SSD) of 15 cm, 25 cm, 35 cm, 45 cm and 55 cm, were utilized to deliver dose-rates of 3.88 Gy/min, 1.42 Gy/min, 0.72 Gy/min, 0.44 Gy/min and 0.29 Gy/min, respectively. For each of the dose-rates five minute exposures were performed in order to evaluate reproducibility and stability of the response. After each measurement, the BeO ceramic was optically bleached with the laser for 5 min in preparation for the next reading.

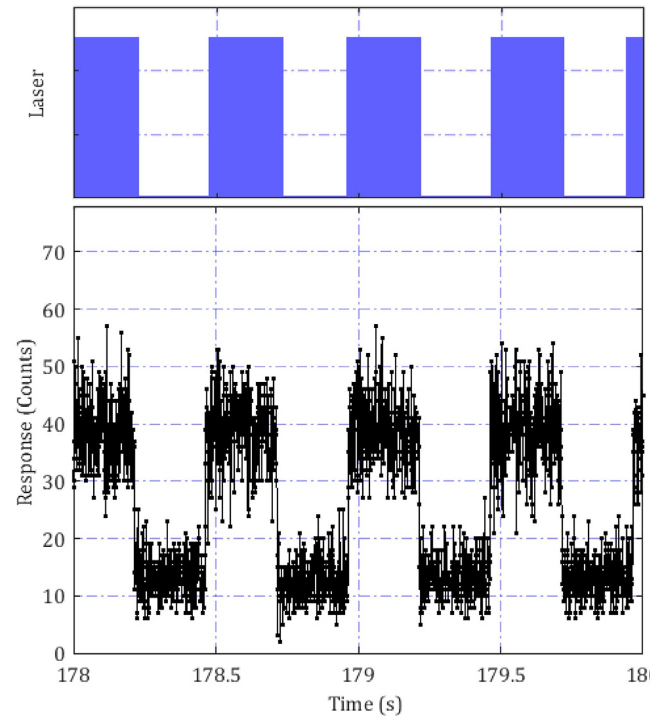

Fig. 2. The real-time OSL during the exposure of 3.88 Gy/min, depicted by the state of the laser [above] and the signal measured by the PMT [below]. By subtracting the count rate measured between the laser pulses from the count rate measured during the laser pulses, an rtOSL signal is obtained.

3. Results

3.1. Real-time OSL

The final RL + Stem and OSL signal was computed and separated as shown in Fig. 3. Also shown is the resulting rtOSL signal which is the OSL signal minus the average of the two neighbouring RL + Stem measurements. Fig. 3 shows the rtOSL to be increasing as the irradiation is occurring. This indicates that the OSL was not being bleached by each laser pulse, further supported by the continual decay in OSL after the exposure to X-rays has ceased.

3.2. Dose-rate response

Fig. 4 shows the rtOSL signal for 5 min exposures at five different dose-rates, performed by increasing the distance between the cone and the detector. The rtOSL was observed to continuously increase as exposure continued. The slope of the rtOSL is reduced for the lower dose-rates, indicating a dose-rate response in the rtOSL. Fig. 5 shows the rtOSL divided by the exposed dose-rate, it can be seen that all five measurements are now coincident with each other. Therefore the rtOSL response is linear with dose-rate.

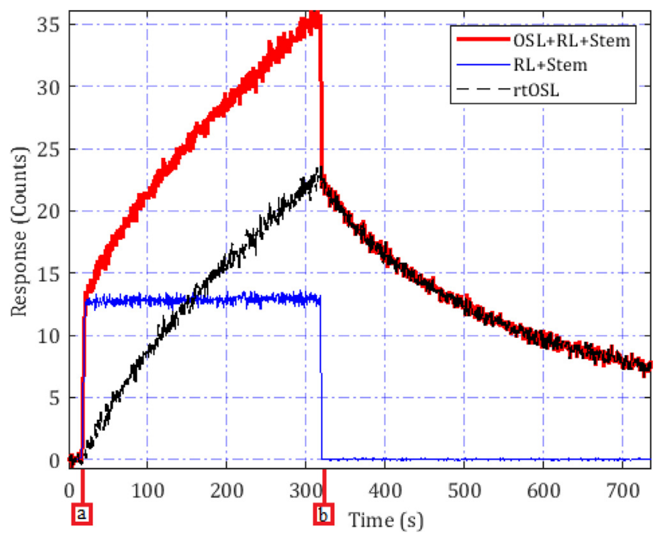

Fig. 3. The RL + Stem, OSL + RL + Stem and rtOSLbtq signals during and after a 300 s exposure of 3.88 Gy/min. Time points a and b indicate the start and stop of the exposure, respectively.

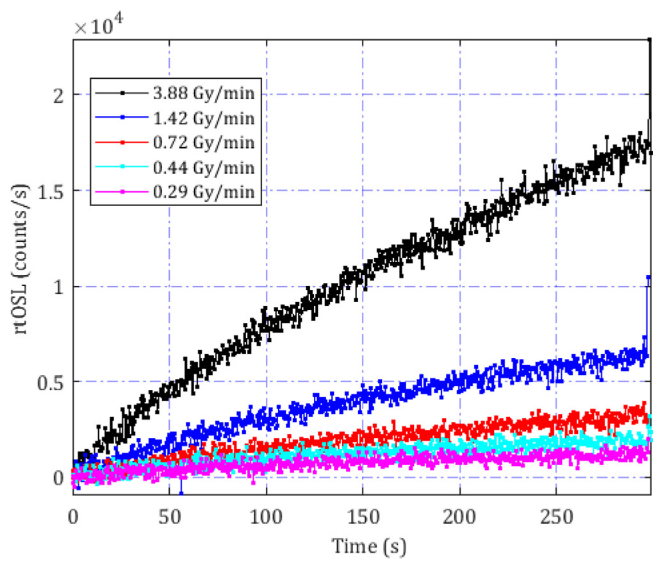

Fig. 4. The rtOSL signal for 5 min exposures at dose-rates of 3.88 Gy/min, 1.42 Gy/min, 0.72 Gy/min, 0.44 Gy/min and 0.29 Gy/min.

The rtOSL observed differs from that observed by Teichmann et al. [6]. Unlike the previous study which observed the rtOSL to first quickly rise and then have a flatter slope, here the rtOSL is observed to continuously rise. This difference may be due to the lower dose-rates utilized by Teichmann et al. [6].

3.3. OSL decay correction

As can be seen from Fig. 5, the rtOSL signal is increasing and is hence sensitive to the accumulated dose, this is due to each laser pulse not completely bleaching the BeO. Fig. 6 shows the rtOSL signal against the accumulated dose to the BeO. As can be seen, the results are not linear and each of the measurements was observed to begin to saturate. This is due to each laser pulse not completely bleaching the BeO material, though it is still stimulating some of the trapped charge. A previous publication investigating Al_2O_3:C utilized a corrected OSL, OSL‘, computed using Eq. (1) [13]. This correction requires a decay factor, F_D, to describe the amount of reduced rtOSL after each laser pulse passes. Fig. 7 shows the rtOSL signal corrected for the decay of the OSL after each pulse, currently using a constant decay factor of 1.0017, hence there is a 0.17% decay of rtOSL after each pulse. Since this decay is applied to each pulse after that additional OSL, the decay factor F_D takes the form $1.0017^{n\text{-}i}$. This single decay factor was observed to correct all of the dose-rate measurements to have a linear response with accumulated dose.

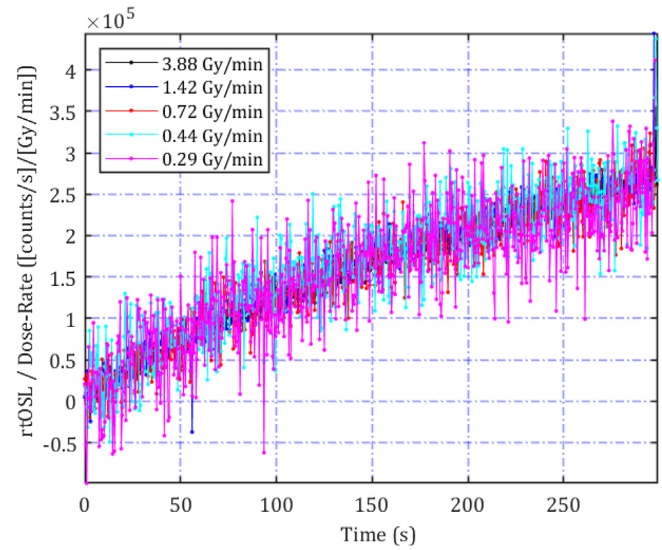

Fig. 5. The rtOSL signal divided by the exposed dose-rate for 5 min exposures at dose-rates of 3.88 Gy/min, 1.42 Gy/min, 0.72 Gy/min, 0.44 Gy/min and 0.29 Gy/min.

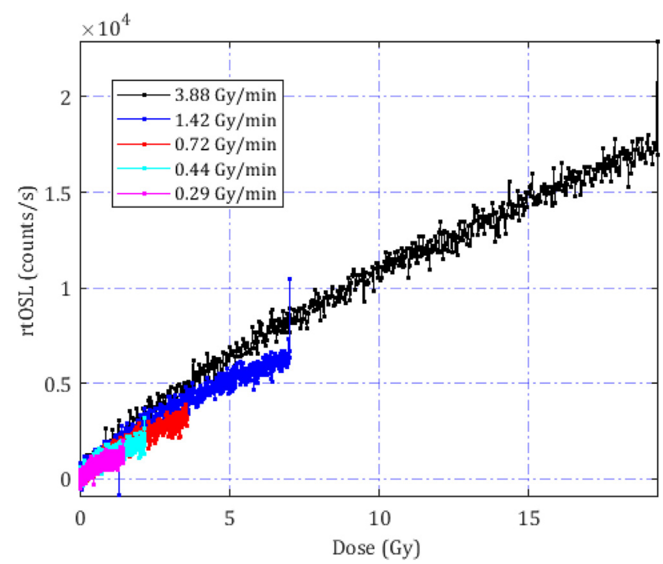

Fig. 6. The rtOSL signal plotted against the accumulated dose for 5 min exposures at dose-rates of 3.88 Gy/min, 1.42 Gy/min, 0.72 Gy/min, 0.44 Gy/min and 0.29 Gy/min.

$$rtOSL'(n) = rtOSL(n) + \sum_{i=1}^{n-1} rtOSL(i) F_D(i, n) \tag{1}$$

where rtOSL′ is the corrected rtOSL signal, and n is the number of the rtOSL pulse being analysed.

3.4. Change in rtOSL (ΔrtOSL)

Averaging is performed to reduce the noise, with an averaging window of 30 s. The change in rtOSL (ΔrtOSL) which is proportional to dose-rate, is calculated by subtracting the current rtOSL pulse reading

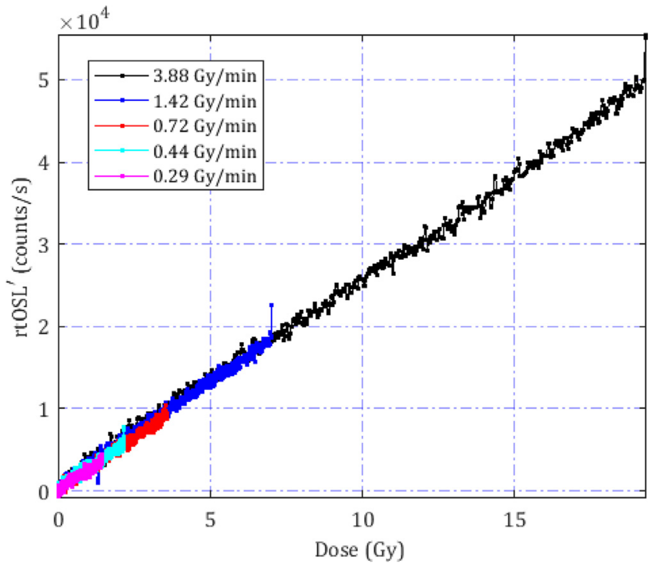

Fig. 7. The *rtOSL*′ signal corrected for the decay of the OSL after each laser pulse for 5 min exposures at dose-rates of 3.88 Gy/min, 1.42 Gy/min, 0.72 Gy/min, 0.44 Gy/min and 0.29 Gy/min.

from the previous pulse. The mean ΔrtOSL for each of the dose-rates is shown in Fig. 8a) where the error bars are one standard deviation of the ΔrtOSL. The RL + Stem response at the different dose-rates are shown in Fig. 8b). Fig. 8c) depicts the ΔrtOSL and RL + Stem response divided by the dose-rate for each of the five dose-rates, normalized to the response at the highest dose-rate. Little variation in the ΔrtOSL response is observed, therefore the ΔrtOSL is shown to have a linear dose-rate response. However, in the case of the RL + Stem, an increased response at the lower dose-rates of 63% is observed. This increase is due to the increased SSD and can be explained by the increase in optical fibre being exposed which is resulting in an increase in stem effect. This is not observed in the ΔrtOSL response and hence the ΔrtOSL is stem effect free.

4. Conclusion

BeO ceramic fibre-coupled luminescence dosimeters have been shown to have favourable energy dependence and show promise for in-vivo dose verification in high dose-rate brachytherapy [4,5]. This system was based on reading the RL for dose-rate measurements, and stimulating the OSL post-irradiation for the accumulated dose. BeO ceramic fibre-coupled luminescence dosimeters have a small size and are capable of real-time measurements, needed for in-vivo dosimetry. One major limitation of this system was the stem effect in the RL measurement, which can be 50% of the signal measured from an Ir-192 source 5 cm away.

In this study, a BeO ceramic fibre coupled luminescence dosimetry system has been developed for real-time OSL dose-rate measurements in order to remove the stem effect. The system has been characterized using a constant dose-rate superficial X-ray beam. It was observed that the change in rtOSL (ΔrtOSL) is linear with dose-rate and is stem effect free. The major limitation with the current system is the temporal resolution. This is required to be improved in order for this system to have a clinical application.

Future work involves utilizing a bifurcated optical fibre in order to have greater physical stability and ease of use. The next stage of this dosimeter will be using a higher power blue laser, which may increase the ΔrtOSL. Finally, in order for this dosimetry system to be utilized in a clinical scenario such as dose verification of brachytherapy treatments, where the energy independence of BeO ceramic will be important, its ability to measure changes in dose-rate will be evaluated.

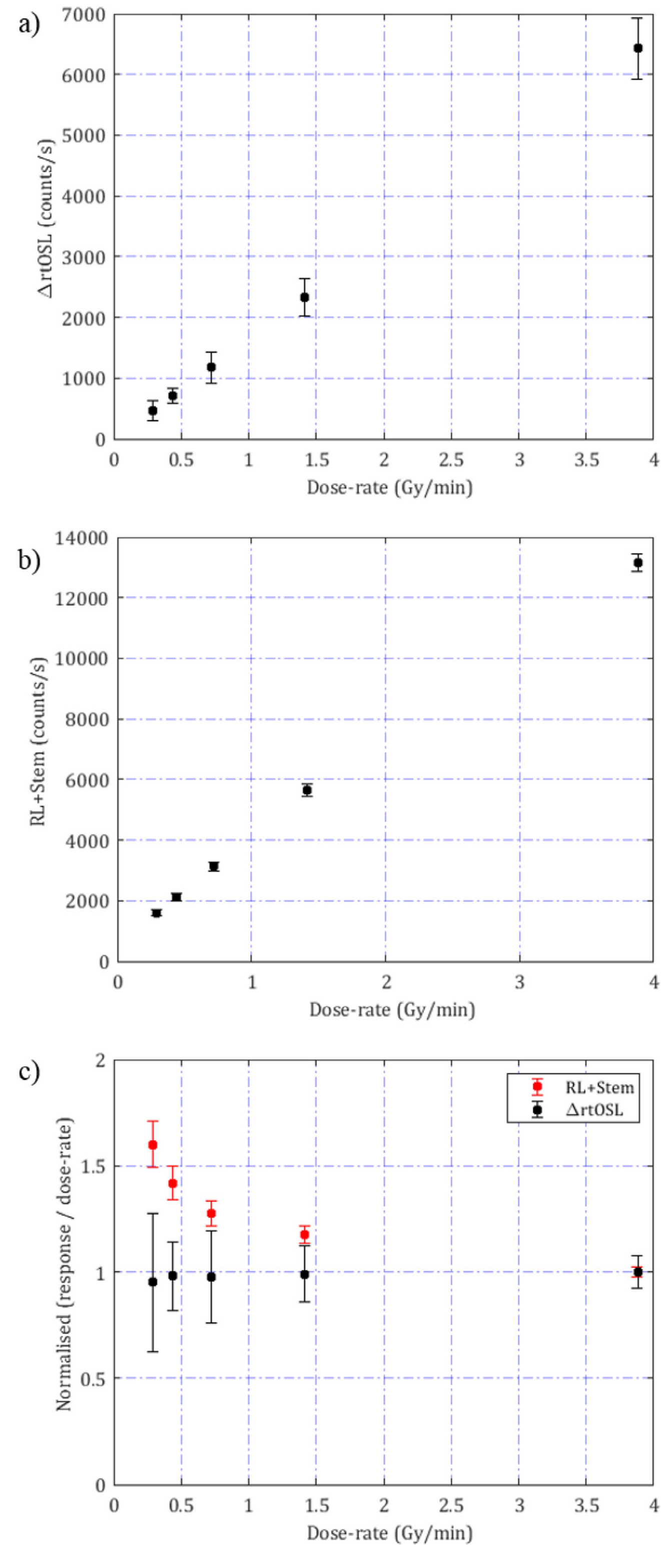

Fig. 8. a) The ΔrtOSL and b) the RL + Stem computed for each of the five dose-rates, c) the RL + Stem and the ΔrtOSL divided by the dose-rate, normalized to the highest dose-rate.

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Disclosures

The authors declare that there are no conflicts of interest related to this article.

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