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Ruby-based inorganic scintillation detectors for ^{192}Ir brachytherapy

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Abstract

We tested the potential of ruby inorganic scintillation detectors (ISDs) for use in brachytherapy and investigated various unwanted luminescence properties that may compromise their accuracy. The ISDs were composed of a ruby crystal coupled to a poly(methyl methacrylate) fiber-optic cable and a charge-coupled device camera. The ISD also included a long-pass filter that was sandwiched between the ruby crystal and the fiber-optic cable. The long-pass filter prevented the Cerenkov and fluorescence background light (stem signal) induced in the fiber-optic cable from striking the ruby crystal, which generates unwanted photoluminescence rather than the desired radioluminescence. The relative contributions of the radioluminescence signal and the stem signal were quantified by exposing the ruby detectors to a high-dose-rate brachytherapy source. The photoluminescence signal was quantified by irradiating the fiber-optic cable with the detector volume shielded. Other experiments addressed time-dependent luminescence properties and compared the ISDs to commonly used organic scintillator detectors (BCF-12, BCF-60). When the brachytherapy source dwelled 0.5 cm away from the fiber-optic cable, the unwanted photoluminescence was reduced from > 5% to < 1% of the total signal as long as the ISD incorporated the long-pass filter. The stem signal was suppressed with a band-pass filter and was < 3% as long as the source distance from the scintillator was < 7 cm. Some ruby crystals exhibited time-dependent luminescence properties that altered the ruby signal by > 5% within 10 s from the onset of irradiation and after the source had retracted. The ruby-based ISDs generated signals of up to 20 times that of BCF-12-based detectors. The study presents solutions to unwanted luminescence properties of ruby-based ISDs for high-dose-rate brachytherapy. An optic filter should be sandwiched between the ruby crystal and the fiber-optic cable to suppress the photoluminescence. Furthermore, we recommend avoiding ruby crystals that exhibit significant time-dependent luminescence.

Keywords

Ruby; inorganic scintillation detector; brachytherapy; in vivo dosimetry; high dose rate brachytherapy; Ir-192

1. Introduction

Radiation detectors consisting of a light-emitting scintillator volume coupled to a fiber-optic cable facilitate the real-time verification of radiation therapy treatments. Inorganic scintillation detectors (ISDs) have demonstrated promise for use in *in vivo* dosimetry and radiotherapy quality assurance routines (Tanderup *et al* 2013, Mijnheer *et al* 2013, O’Keeffe *et al* 2015, Kertzscher *et al* 2014b). Both ISDs and plastic scintillation detectors (PSDs) (Beddar *et al* 1992c, 1992b) possess several characteristics that make them suitable for *in vivo* brachytherapy (BT) dosimetry (Tanderup *et al* 2013). For instance, their small size allows them to be placed inside narrow BT catheters inserted in the tumor region, and real-time monitoring of the detector response facilitates online error detection. The response of ISDs to absorbed dose in water is, in contrast to that of PSDs, dependent on the photon energy spectrum (Rogers 2009), while both ISD and PSD responses exhibit temperature dependence (Edmund and Andersen 2007, Beddar 2012, Wootton and Beddar 2013, Buranurak *et al* 2013). However, the energy and temperature dependences can be corrected for with fairly straightforward methods (Wootton and Beddar 2013, Reniers *et al* 2012).

Inorganic scintillators have 2 further advantages that make them more promising than PSDs for *in vivo* BT dosimetry. First, a wide variety of scintillator materials emit in the red wavelength region, i.e., 600–750 nm (Jordan 1996, Molina *et al* 2012, Veronese *et al* 2014, McCarthy *et al* 2013, Teichmann *et al* 2013, Martinez *et al* 2015). Scintillation in longer wavelengths is advantageous for dosimetry because it greatly simplifies the removal of the most important sources of measurement uncertainty for scintillation detectors—the Cerenkov and fluorescence effects (Beddar *et al* 1992a, Theriault-Proulx *et al* 2013a), which exhibit a continuous emission spectrum most prominent in the blue region. The use of a red emitter together with a filter that suppresses the blue part of the light spectrum allows filtration of most of the unwanted Cerenkov and fluorescence light produced in the fiber-optic cable that links the detector volume to a photodetection system. In this article, the Cerenkov and fluorescence light together will be referred to as the stem signal.

The second advantage of inorganic scintillators is the wide selection of materials that yield scintillation intensities (photons/MeV) up to 1 order of magnitude higher than those of organic scintillators (Derenzo *et al* n.d.). Inorganic scintillator materials are denser than organic materials and produce higher absorbed doses and scintillation intensities. Their superior light output increases the signal-to-noise ratio and the dynamic range of the detector system, a crucial feature for *in vivo* dosimetry of typical BT treatment plans (Kertzscher *et al* 2011b) that allows measurement of smaller dose rates for positions remote from the detector volume and larger dose rates when the source is near the detector.

As previously shown for inorganic scintillator materials that are denser than water, ISDs exhibit higher sensitivity to low-energy radiation than ionization chambers (Molina *et al* 2013, Martinez *et al* 2015). The response of ISDs characteristically diverts towards higher values with respect to ionization chambers as the secondary radiation component becomes more dominant than the primary radiation component, which leads to an overestimation of the absorbed dose to water. The characteristic ISD response would likely be significant in

BT as the BT source would move towards positions farther away from the ISD, where the secondary radiation component is more dominant. The characteristic response is a disadvantage for ISDs which needs to be characterized and corrected for, e.g. using a correction curve described in (Reniers *et al* 2012).

Ruby (Al_2O_3 doped with Cr^{3+} ions) is an inorganic scintillator material that exhibits a narrow radiation-induced emission spectrum, with a maximum value at 694 nm. Jordan (Jordan 1996) was the first to study ruby for radiation dosimetry in photon and electron external beam radiotherapy and demonstrated that ruby-based ISDs agree with reference ion chamber data. Jordan also presented a method to suppress the unwanted additional photoluminescence signal in the ruby crystal generated by the transmission of the stem signal back to the scintillator. The photoluminescence signal is proportional to the absorbed dose in the fiber-optic cable and can therefore distort the desired radioluminescence signal induced in the ruby crystal, which is proportional to the absorbed dose in the detector volume. Teichmann *et al.* (Teichmann *et al* 2013) further investigated ruby-based ISDs for external beam radiation sources and highlighted that ruby crystals can exhibit unwanted time-dependent luminescence properties that probably depend on the admixture of impurities other than Cr^{3+} in the crystal lattice (Bessonova *et al* 1979). Both Jordan and Teichmann *et al.* used the temporal gating technique to suppress the stem signal. As described in (Andersen *et al* 2011), that technique requires pulsed radiation sources and is therefore not applicable for BT.

Ruby's narrow emission spectrum near 694 nm overlaps less with the stem signal than the emission spectra of other scintillators used in BT dosimetry, which emit at the shorter wavelengths where the stem signal is more prominent (Therriault-Proulx *et al* 2011b, Kertzscher *et al* 2011a, Santos *et al* 2015). Furthermore, the high density of the ruby crystal may provide higher scintillation intensities than do organic scintillators. Combined with the favorable emission spectrum, a sufficiently large ruby scintillation intensity would allow suppression of the unwanted stem signal to negligible levels in a single readout channel. This could be accomplished with a narrow band-pass filter to monitor the wavelength region near the emission peak of the ruby signal. Such a simple design could facilitate the development of dosimetry systems that employ the standard one-channel electrometers that are already available in the vast majority of radiotherapy clinics and could encourage the dissemination of *in vivo* dosimetry technology to more clinics (Tanderup *et al* 2013, Kertzscher *et al* 2014b). Furthermore, sufficiently large light outputs also eliminate the need for high-sensitivity photodetectors, making such dosimetry systems more affordable. These advantages make ruby-based detectors attractive for BT since they can provide affordable technology that can measure the absorbed dose precisely in large dose ranges that are common in BT.

In this study, we investigated the potential of ruby as an ISD material for high-dose-rate (HDR) BT dosimetry. We compared the scintillation intensities of ruby-based ISDs and PSDs made of common organic scintillators. We also characterized several unwanted luminescence properties that may compromise the accuracy of ruby-based ISDs. Finally, we present detector probe manufacturing methods that help to increase the signal collection and adapt the photoluminescence suppression concept introduced by Jordan (Jordan 1996).

2. Materials and methods

2.1 Luminescence properties of ruby

This section introduces luminescence properties of ruby which may significantly impact the accuracy of dose measurements in HDR BT. The ruby ISD probes consisted of a ruby crystal optically coupled to a clear fiber-optic cable. The energy loss of ionizing radiation in ruby produces radioluminescence, which gives rise to scintillation in a narrow luminescence band centered at 694 nm due to the ${}^2E \rightarrow {}^4A_2$ transition. However, ruby can also undergo the transition from the ground state 4A_2 to excited states 2E , 2T_1 , 2T_2 , 4T_1 , 4T_2 ; the latter 2 transitions dominate and correspond to the absorption of energy quanta in the blue and yellow-green wavelength regions, respectively (Henderson 1995). The higher excited states decay non-radiatively to the 2E excited state, from which ${}^2E \rightarrow {}^4A_2$ transitions occur, producing photoluminescence, i.e., the excitation of the ruby crystal by ambient visible light that generates luminescence at 694 nm. Radiation-exposed ruby crystals also undergo other energy transfers, resulting in temporally non-constant scintillation and afterglow effects, which will be addressed in detail below.

Ionizing radiation also generates a stem signal composed of Cerenkov and fluorescence light in the fiber-optic cable (Beddar *et al* 1992a, Therriault-Proulx *et al* 2013b); the stem signal exhibits a continuous emission spectrum most prominent in the blue region. Its intensity is proportional to the absorbed dose in the fiber-optic cable and is therefore prominent when the BT source position is near the cable and far from the ruby crystal.

Our intention was to measure the absorbed dose in the detector volume by monitoring the radioluminescence which is induced by ionizing radiation. The stem signal is proportional to the absorbed dose in the fiber-optic cable rather than in the detector volume and is therefore considered a background signal. Photoluminescence is also considered a background signal because it is generated by the stem signal and is, therefore, also proportional to the absorbed dose in the fiber-optic cable. The non-constant scintillation and afterglow effects are also problematic because they cause a false response in the detector volume when the source changes from one dwell position to another during afterloaded BT. To maximize the dose measurement accuracy, we designed the ruby ISDs with the specific goal of minimizing the background signals and time-dependent effects.

2.2 Detector probe designs and signal acquisition

Both the ISD and PSD probes were composed of a single scintillation detector volume coupled to a 15 m-long fiber-optic cable (ESKA GH-4001, Mitsubishi Rayon Co. Ltd., Japan). The core of the fiber-optic cable was 1 mm in diameter and made of poly(methyl methacrylate) (PMMA). The scintillation light emitted from the detector volume was transmitted through the fiber-optic cable and collected by a photodetector system. Throughout the experiments, the scintillation light was collected either by a charge-coupled device (CCD) camera (Luca S 658M, Andor Technology Ltd., UK) or a spectrometer spectrograph (Shamrock SR-163i, Andor Technology Ltd.). The end of the fiber-optic cable of all ISD and PSD probes were terminated with connectors of the SMA standard (product number 11040A, Thorlabs Inc., USA) and polished on polishing sheets (product numbers

LFG03P, LFG1P, LFG3P, and LFG5P, Thorlabs Inc., USA). The SMA connectors and carefully inspected polishing facilitated reproducible optical coupling between the detector probes and the CCD camera or spectrometer.

We used 2 organic and 1 inorganic detector material (see table 1). The organic detector materials BCF-12 and BCF-60 (Saint-Gobain Crystals, France) were made of polystyrene, and the inorganic material was ruby crystals. The ruby crystals, Al_2O_3 doped with Cr^{3+} (0.5%), were obtained in spherical and half-spherical shapes (product numbers 43639 and 49558, respectively, Edmund Optics Inc., USA).

Three detector probe designs were used (see figure 1). Probe type A (figure 1, left) consisted of a scintillator that was coupled directly to the surface of the fiber-optic cable with transparent glue (NOA68, Norland Products Inc., USA) that was cured with ultraviolet light. Black epoxy was used to protect the optical coupling from mechanical stress and to prevent the ISD from ambient light contamination. The manufacturer of the fiber-optic cable (Mitsubishi Rayon Co. Ltd.) incorporated the cladding to facilitate internal reflection in the transmission cable and the jacket to protect the cable from mechanical stress and ambient light. Probe types B and C were developed for the ruby detectors only, since the BCF-12 and BCF-60 detectors were used as references. Probe type B (figure 1, middle and right columns, top row) was identical to type A except that it had a layer of reflective paint covering the ruby scintillator (EJ-510, Eljen Technology, USA) to enhance the signal-to-noise ratio. The transparent glue (NOA68, Norland Products Inc., USA) was used to couple the ruby crystal with the fiber-optic cable.

The principle behind probe type C (figure 1, middle and right columns, bottom row) was previously implemented by Jordan (Jordan 1996). Probe type C was identical to type B except for a thin plastic long-pass optic filter sandwiched between the scintillator and fiber-optic cable (Supergel 27, Rosco Laboratories Inc., USA). The transmission efficiency of the filter was ~85% about the 694 nm ruby emission peak, 50% at 658 nm, and < 10% at < 615 nm. The filter prevented most Cerenkov and fluorescence light from reaching the ruby crystal, thereby suppressing the photoluminescence in the ruby crystal. Since the optic filter reduced the amount of stem signal reaching the ruby crystal and also transmitted wavelengths about the ruby emission peak, the incorporation of the filter ensured that the transmitted detector signal originated from radioluminescence rather than from photoluminescence. The transparent glue (NOA68, Norland Products Inc., USA) was used to couple the ruby crystal with the optic filter, and the optic filter with the fiber-optic cable.

The shapes of the detector volumes (see table 1) were governed by the commercial availability of the detectors and by probe design requirements. The ruby detectors were available in spherical and half-spherical shapes, and the organic scintillators were available in cylindrical fibers. The diameters of all detector volumes were 1 mm because that was the core diameter of the fiber-optic cable. The length of the organic scintillators was 1 mm.

Eight distinct probe types (combinations of detector material and probe design) were used in this study. Each probe type was manufactured in multiples of 3, so a total of 24 detector

probes was used (3 BCF-12, 3 BCF-60, 3 ruby half-sphere type A, 3 ruby sphere type A, etc.).

Hereafter, a scintillating detector volume optically coupled to a fiber-optic cable will be referred to as a “detector”. In addition to the 24 detectors, 2 probes composed of a fiber-optic cable with no detector attached to its distal end were used. Those probes will be referred to as “bare fibers”.

2.3 Measurements

All experiments used a Nucletron MicroSelectron v2 HDR afterloader. The air-kerma strength of the ^{192}Ir source was between 17.6 and 40.0 mGy m² h⁻¹ throughout the experiments.

2.3.1 Signal strengths of scintillator detectors—The relative signal strengths of the different detectors were measured to determine how the signal strength of ruby-based ISDs compared with that of PSDs made of BCF-12 and BCF-60. The assessment of the relative signal strength was substantiated with individual measurements for all 3 multiples of each detector probe material and design (figure 1).

All measurements were performed in a rigid polymer-based and water-equivalent phantom (Solid Water, Gammex, USA) to enable robust and repeatable placement of the source applicator and detector probe. The source applicator and the detector probe were placed in parallel grooves 2 cm apart. At this distance, the BT source dwelled at the nearest position from the detector volume (2 cm) at which a < 5% maximum variation of the absorbed dose in the scintillating detector volume could be assured, given the ± 0.02 cm freedom of movement of the BT source inside the applicator. Measurements of the Cerenkov and fluorescence signals were also obtained using a bare fiber.

The method described in (Beddar *et al* 1992c, 1992b) was adapted in this study to remove the stem signal background from the ISD and PSD measurements. The detector in the studies by Beddar *et al.* incorporated two probes that were monitored simultaneously: one consisting of a plastic scintillator coupled to the fiber-optic cable, and one consisting of a bare fiber that was adjacent to the fiber-optic cable of the scintillator probe. The stem signal was removed from the scintillator probe by subtracting the signal of the bare fiber from the scintillator probe signal. In this study, two adjacent fiber-optic cables are prone to generate different amounts of stem signals because only a small misalignment may in the steep dose gradient near BT sources cause large differences in the absorbed dose in the fiber-optic cables. Measurements were therefore performed with one probe at the time, to assure that the fiber-optic cables in the ISDs, PSDs and bare fibers were exposed identically to the same dose gradient conditions.

Signals from the detectors and bare fibers and electronic noise were collected with the CCD camera, which was equipped with a 25-mm (F1.8) lens (Computar, USA) and a 25-mm spacer. The signal strength for each detector was defined as the sum of pixel values in a 140 × 140 pixel region of interest, which contained the entire signal spot that was projected on the CCD chip (Klein *et al* 2011). A temporal median filtering algorithm was adapted to

improve the accuracy of the signal strength assessment by eliminating the impact of potential outlier pixel values caused by transient noise from, for example, stray radiation from the BT source or cosmic rays incident on the CCD camera (Archambault *et al* 2008). Five consecutive images were acquired for each detector with a 10 s CCD camera exposure time and under identical irradiation conditions, i.e., without retracting the source or adjusting the detector setup. Each pixel value corresponded to the median value from the 5 images. To further improve accuracy, 25 hot pixels of each image were omitted from the analysis. The 10 s exposure time resulted in a $< 0.3\%$ statistical uncertainty for 10 consecutive measurements after the filtering algorithm and hot pixel omission were applied.

The absorbed dose uncertainty caused by the positional uncertainty of the BT source was determined by taking 10 consecutive measurements between which the source retracted into the afterloader. After we subtracted the statistical uncertainty from the measurements, the positional uncertainty amounted to 0.3%. The measurement variability caused by variations in the placement of the detector probe in the phantom and in the connections and disconnections of the detector probe with the CCD camera setup was obtained by repeating the placement and connection procedure 10 times with a high-signal intensity signal setup, which generated a negligible statistical uncertainty and by eliminating the positional uncertainty of the BT source from the calculations. The connection uncertainty was $< 0.1\%$.

2.3.2 Scintillator and background signal components—The total signal of the detector system consisted of light originating from the scintillator volume and from the fiber-optic cable. As discussed previously, the signal of interest was the scintillation induced in the detector volume by ionizing radiation, not the stem signal in the PMMA cable or the photoluminescence signal induced in the ruby crystal by the stem signal. Both the stem signal and the ruby photoluminescence are unwanted background signals that are prominent when the BT source position is near the fiber-optic cable and far from the ruby crystal.

The relative contributions of the scintillator and background components were estimated using measurements of their emission spectra and signal intensities. The emission spectra of the ruby, BCF-12, and BCF-60 scintillator volumes were measured with the spectrometer with the BT source and the detector volumes separated by 0.5 cm in the phantom. Although the stem signal accounted for $< 1\%$ of the signal for the BCF-12 and BCF-60 detectors and even less for the ruby ISDs, we subtracted the emission spectrum of the stem signal, obtained under identical irradiation conditions using the bare fiber, to eliminate its influence. The signal strength per absorbed dose was acquired for each detector, using the signal strengths measured with the CCD camera, and the absorbed dose in the scintillating detector volume calculated with the TG-43 protocol (Rivard *et al* 2004). The measured emission spectrum of each detector material was normalized to the corresponding signal strength per absorbed dose value. As a result, normalized emission spectra were obtained, where each wavelength bin value was proportional to the absorbed dose in the detector volume. Such normalized spectra were obtained for various attenuations of the PMMA fiber-optic cable (0, 2, 5, 10, 15 m). All spectra were corrected for the quantum efficiency of the CCD camera and the spectrometer system. It should be noted that the bare fiber signal obtained for 0 m attenuation simulates the signal generation corresponding to irradiation of a ~ 15 cm portion of the fiber-optic cable.

The normalized spectrum for the stem signal was obtained in the same manner as for the detectors, but using the bare fiber instead of the detector probes. Furthermore, instead of calculating the point dose, we calculated a line integration of the absorbed dose in the fiber-optic cable. The line integration corresponded to the sum of point dose calculations taken at every 0.1 cm along 10 cm of the fiber-optic cable (starting at 0 cm).

The ruby photoluminescence signal was measured with the spectrometer in experiments in which the fiber-optic cable was irradiated while the ISD probe tip, i.e., the scintillating detector volume, was shielded from the BT source using lead blocks and a lead container. The photoluminescence signal was extracted from 4 measurements in which the setup configurations shown in figure 2a were used. The 4 measured spectra, M_a , M_b , M_c , and M_d , were obtained with the following configurations:

- M_a : Ruby ISD probe, configuration 1;
- M_b : Bare PMMA fiber-optic cable, configuration 1;
- M_c : Ruby ISD probe, configuration 2;
- M_d : Bare PMMA fiber-optic cable, configuration 2.

Both photoluminescence and stem signals were generated in M_a . Therefore, the signal M_b was subtracted from M_a to remove the stem signal. Although the ISD probe tip was shielded from the BT source, the signal M_c was measured to obtain the potentially significant ruby radioluminescence signal induced by stray radiation incident on the detector volume. Although the residual stem signal in configuration 2 was negligible, M_d was subtracted from M_c to eliminate any remaining stem signal. One spectrum measurement (M_a , M_b , M_c , and M_d) corresponded to a spectrometer measurement acquired during 3 consecutive 30 s exposures throughout which the irradiation conditions were not modified. The median value of each spectrum bin value was chosen to define the final measured spectrum.

The spectrum of the unwanted ruby photoluminescence (S_{PL}) in the ruby ISDs was defined as

$$S_{PL} = M_a - M_b - (M_c - M_d)$$

which described only the ruby photoluminescence since the stem signal (M_b) and residual ruby excitation ($M_c - M_d$) were subtracted. The S_{PL} spectra were measured for all 3 multiples of each of the ruby ISD types A and B (described in section 2.2, i.e., for all combinations of filtered and unfiltered spherical and half-spherical ruby probes). The final S_{PL} corresponded to the mean value of the 3 measured spectra for each detector type. Each final S_{PL} was normalized to the CCD camera signal strength of the ruby photoluminescence per absorbed dose in the fiber-optic cable.

Under the assumption that each signal component was proportional to the absorbed dose, their relative signal contributions were estimated for each BT source position based on the absorbed dose in the detector volume (scintillator signal) and PMMA fiber-optic cable (stem signal and ruby excitation). The signal components were estimated at the vicinity of the

detector probe tip, assuming no attenuation in the PMMA fiber-optic cable beyond the 15 cm irradiated portion, and for 2, 5, 10, and 15 m PMMA attenuation.

2.3.3 Time-dependent luminescence properties—The time-dependent luminescence properties of the ruby ISDs, i.e., the temporally non-constant scintillation and the afterglow, were characterized for all 18 ruby ISDs in experiments using the setup shown in figure 2b (right). The ruby detector volume and the BT source catheter were separated by 1 cm on a rigid plastic phantom and oriented in opposite directions to avoid stem signal contamination while the source was moving along the BT source applicator. Five-centimeter-thick lead bricks were placed on each side of the BT catheter, 2 cm away from the intended source position. The purpose of the lead bricks was to shield the ISD probe so that the afterglow could be monitored as early as possible after the source had retracted from the dwell position. Three detector probes were used as triggers in the experiments (2 are shown in figure 2b). Two trigger detectors were placed on the BT source catheter on each side of the lead bricks and 1 (not shown) on the source transfer tube at the exit point of the afterloader. The outputs of the ruby ISD and the 3 trigger detectors were continuously and simultaneously monitored with the CCD camera using a custom-made template to which the detector probes could be connected. The setup allowed for monitoring both when the source moved toward or away from the dwell position and when it passed by each trigger detector, without requiring a communication line with the afterloader. The trigger detectors were fiber-coupled detectors which did not exhibit any significant afterglow.

The afterglow was measured by continuously monitoring the ruby ISD signal starting ~10 s before the BT source retracted from the dwell position into the afterloader and for up to ~500 s thereafter. The trigger detectors provided time stamps indicating when the BT source passed by each side of the lead bricks and when it reached at the exit of the afterloader. Separate measurements showed that the residual radiation at the point of the ruby ISD probe tip was negligible for afterglow measurements when the source was on the outside of the lead brick barrier (trigger detector #2 in figure 2b). The measurements also showed that it took 0.1 seconds for the BT source to cross the lead brick barrier once the retraction had started and 1.9 seconds to reach the afterloader.

The non-constant scintillation was measured by monitoring the ruby ISD signal starting ~10 seconds before the BT source reached the dwell position and for up to ~520 seconds thereafter, for an absorbed dose of ~65 Gy. None of the 18 ruby ISDs had been irradiated during a period 3–7 months prior to the measurements. One of the ISDs that exhibited strong time-dependent characteristics was irradiated a second time after a 500 s pause subsequent to the first irradiation. The re-irradiation was performed to investigate if a pre-irradiation of the ruby crystals would remove the time-dependence, as is the case for carbon doped Al_2O_3 crystals (Andersen *et al* 2011).

3. Results

3.1 Detector probe types

The radiation-induced emission spectra of the detector materials and the PMMA fiber-optic cable are shown in figure 3. The emission spectra have been corrected for the quantum

efficiency of the CCD camera and the diffraction grating of the spectrometer and for the attenuation by the 15 m PMMA fiber-optic cable. The measurements revealed that the reflective paint coating on the ruby detector volume (see figure 1) did not modify the emission spectra of the ruby-based ISDs (figure 3, right-hand plot). The optic filter sandwiched between the scintillator and PMMA fiber-optic cable (figure 3, right-hand plot) altered the emission spectrum of the ruby-based ISDs, as the filter suppressed shorter wavelengths more than longer ones.

3.2 Signal strengths of scintillation detectors

The signal strengths for all detector probes, including the scintillation between 400 and 707 nm, are shown in figure 4. The uncorrected signal strength values (figure 4, top) indicated that the signal of the BCF-60 probe was half as strong as that of the BCF-12 probe. The signal strengths of the ruby-based ISDs without filter or reflective paint were similar to that of the BCF-12 detector. However, the total volume of the ruby sphere and half-sphere were 66% and 33%, respectively, of the BCF-12 detector (see table 1); hence, the signal yield from the ruby detectors would likely be larger than the BCF-12 signal if all detector volumes were the same.

The reflective paint on the ruby-based ISDs increased the signal by a factor of close to 3, so the measured signal strength of the ruby-based ISDs with reflective paint was approximately 3 times larger than that of the BCF-12 detector (figure 4, bottom, insert). As seen in figure 4 (top), the introduction of an optic filter between the scintillator and the PMMA fiber-optic cable may have caused an increase in the variation of the signal strength, but, on average, not a substantial decrease in the signal itself. The signal variation may have originated from the limited reproducibility of the optical coupling between the ruby crystal, optic filter and fiber-optic cable. For instance, a slight offset between the ruby crystal and the fiber-optic cable was noted for the ruby half-sphere ISD with reflective paint and optic filter that generated the smallest scintillation signal (see figure 4). The reproducibility could be improved if the optic filter had the same diameter as the fiber-optic cable and the scintillator, because that would simplify to align the three components, e.g. by stacking them in 1 mm inner diameter plastic tubing. Optic filters with 1 mm diameters are not common. However, a sharp 1 mm diameter hole-puncher with high geometric tolerance could aid cutting the plastic optic filters used for the ruby ISDs into 1 mm diameter pieces. Alternatively, as previously performed by Jordan (Jordan 1996), a dye that absorbs < 650 nm and transmits > 650 nm wavelengths can be mixed with the glue used to couple the fiber-optic cable and the ruby crystal. The dye-mixed glue would eliminate the need for a 1 mm diameter filter, and simplify the manufacturing procedure into aligning two components (ruby crystal and fiber-optic cable) rather than three.

The signal strengths of the half-spherical and spherical ruby detectors were, respectively, 8 and 6 times larger than that of BCF-12 when the 15 m attenuation only was included, i.e., when the volume and quantum efficiency of the CCD camera were corrected (figure 4, bottom). The signal strength of the half-sphere was ~30% larger than that of the sphere, indicating that the optical coupling of the half-sphere with the PMMA fiber-optic cable was more efficient than that of the sphere.

Given the wavelength dependence of the attenuation of the PMMA cable (available from the manufacturer: Mitsubishi Rayon Co. Ltd., Japan), our calculations showed that the signal between 400 and 707 nm would increase by a factor of 3.7 for the ruby ISDs, by a factor of 1.6 for the BCF-12 PSD, and by a factor of 1.5 for the BCF-60 PSD if the fiber-optic cable was shortened from 15 to ~0 m. For 20 nm wavelength regions centered at 697, 420, and 525 nm, the signal would increase by a factor of 4.4, 1.8, and 1.3 for the ruby ISDs, the BCF-12 PSD, and the BCF-60 PSD, respectively. Shortening the fiber-optic cable would produce signals between 400 and 707 nm of up to 30 times the BCF-12 signal (15 m attenuation) for the ruby half-sphere (0 m attenuation) and up to 20 times the BCF-12 signal (15 m attenuation) for the ruby sphere (0 m attenuation).

3.3 Scintillator and background signal components

The ruby scintillation and background signal components were obtained for detector positions from -10 to 10 cm in the z-direction around the BT source, which was positioned at $z = 0$ cm, and for detector positions 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 cm away from the BT source in the x-direction ($y = 0$ cm). Figure 5 shows the results for the ruby half-sphere ISD when the detector and BT source catheter axes were separated by 0.5 cm. The stem signal obtained simulates the signal generated with irradiation of a ~15 cm portion of the fiber-optic cable.

The top row of figure 5 shows the signal composition when the ISD was positioned at $z = 5.0$ cm, i.e., when the source was positioned 5.0 cm along the fiber-optic cable. In the wavelength region near 700 nm, the unwanted ruby photoluminescence was more significant than the stem signal when no filter was used (left) and less significant than the stem signal when the filter was sandwiched between the detector and fiber-optic cable (right). As expected, the wavelength spectrum of the ruby photoluminescence was similar to that of the radioluminescence, peaking at 694 nm.

The bottom row of figure 5 shows the contribution of each signal component to the total ruby ISD signal. The signal contributions were calculated for wavelengths between 687 and 707 nm, simulating a 20 nm optical band-pass filter (indicated by the dashed vertical lines on the top row). The plots show the signal contribution for BT source positions between 0 and 8 cm along the fiber-optic cable. The results demonstrate that the unwanted ruby photoluminescence was > 5% of the total signal for z-distances > 7 cm when no filter was used (left) and was reduced to < 1% when the filter was incorporated (right). The ruby photoluminescence was 1.6 times more significant than the stem signal when no filter was used and 0.2 times the significance of the stem signal when the filter was incorporated. In addition, the photoluminescence signal of the half-sphere was larger than that of the sphere, further indicating that the optical coupling of the half-sphere with the PMMA fiber-optic cable was more efficient than that of the sphere.

The stem signal was suppressed by the 20 nm band-pass filter to < 3% as long as the source distance was < 7 cm. Our calculations showed that the stem signal increased to values up to 5% and 7% if the band-pass wavelength region was widened to 670–707 nm and 650–707 nm, respectively. The stem signal suppression therefore benefits from narrowing the wavelength region of the band-pass filter to 20 nm. Additionally, if a wide band-pass

wavelength region is used, the stem signal component increases substantially as the length of the PMMA fiber-optic cable increases towards 15 m because the attenuation in PMMA penalizes light signals with wavelengths near red more than it does those in the blue and green regions.

3.4 Time-dependent luminescence properties

Our results showed that the ruby crystals exhibited different time-dependent luminescence characteristics. Of the 18 ruby crystals included in this study, 3 exhibited weak time-dependence (2 type A and 1 type C half-spherical ISDs), while the remaining 15 exhibited strong time-dependence (6 half-spherical and 9 spherical ruby crystals). Although the ruby crystals with weak time-dependence were half-spherical, most half-spherical crystals (6 out of 9) exhibited strong time-dependence. Therefore, we were not able to identify if a ruby crystal would exhibit weak or strong time-dependence prior to taking initial test measurements.

The time-dependence characteristics for all ruby ISDs are compared in figures 6 and 7. To clarify the differences in time-dependence, one of the ruby ISDs with small dependence (Ruby #1, type A probe with half-spherical crystal, red dotted line in figures 6 and 7) and one of the ISDs with large dependence (Ruby #2, type B probe with spherical crystal, thick blue solid line in figures 6 and 7) have been selected as representative examples. The remaining ruby ISDs (Ruby #3 to #18, thin solid black line in figures 6 and 7) and the time-dependence of the re-irradiated ruby crystal (Ruby #2, yellow dashed line) are also shown for comparison.

The non-constant scintillation of Ruby #2 caused its scintillation intensity to steadily increase during irradiation, as shown in figure 6 of the scintillation intensities for the 18 ruby ISDs normalized to the maximum intensity within the first 50 Gy. This effect would introduce substantial uncertainty in BT dosimetry since the radioluminescence signal increased substantially during the initial minute of irradiation. As a result, Ruby #2 would generate a temporally unstable dose reading, for instance, if the BT source were moved to a dwell position closer to the ISD position. As shown in table 2, the dose measurement signal of the ISD based on Ruby #2 increased by 9% after the first 10 s at a BT source dwell position located 1 cm away from Ruby #2. In contrast, the Ruby #1 signal changed by 1–2 % during 200 s (24 Gy) irradiation. As shown in figure 6 (yellow dashed line), the strong non-constant scintillation characteristics of the Ruby #2 crystal sustained during the second irradiation, during which the radioluminescence signal was ~4% greater than during the first irradiation. The pre-irradiation protocol (Andersen *et al* 2011) is therefore not recommended for the ruby ISDs.

The afterglow of Ruby #2, as shown in figure 7, was a significant source of uncertainty for BT dosimetry because it generated a signal of ~6% of the total signal after the BT source had retracted from its dwell position (figure 7, right). If the source instead had moved away from the ruby ISD to a new dwell position, the afterglow would have been superpositioned over the new radioluminescence signal, causing a signal overestimation. The measurements showed that the emission spectrum of the afterglow signal was identical to that of the radioluminescence (left plot, left insert) and that it could therefore not be filtered out, for

example, with an optical band-pass filter. The time constants ($T_{1/2}$) of the afterglow that were measurable with the experimental procedures used were 1, 8, and 45 seconds (left plot, right insert). The time constants were retrieved from fitting a 2-term exponential function, i.e. $y = Ae^{at} + Be^{bt}$, to the data in two time-ranges ($t < 9$ s and $t > 8$ s).

4. Discussion

Our experiments with a ruby-based ISD exposed to an ^{192}Ir HDR BT source suggest strategies for circumventing and eliminating unwanted luminescence properties that compromise dose measurement accuracy. The results demonstrate that ruby-based ISDs can generate signal strengths about 1 order of magnitude larger than those generated by organic PSDs. Our study also highlighted that the photoluminescence of ruby and time-dependent luminescence properties must be addressed if ruby-based ISDs are to be successfully implemented in *in vivo* dosimetry during HDR BT. The temperature dependence of radiation-induced luminescence properties in ruby, e.g., scintillation yield and relaxation times, has previously been studied (Levine and Subramanian 1966, Jordan 1996, Bessonova and Sobko 1980). It was not within the scope of this study to characterize the temperature dependence of ruby for ^{192}Ir BT sources. However, characterization of both the temperature and energy dependence of ruby with ^{192}Ir BT sources will be necessary so that corrections like those described elsewhere (Wootton and Beddar 2013, Reniers *et al* 2012) can be applied to *in vivo* dosimetry.

Several strategies could be used to adjust for the scintillation yield, photoluminescence suppression, stem signal suppression, and time-dependent luminescence properties of ruby ISDs. *In vivo* dosimetry performed with an ISD would benefit greatly from a detector volume with a large scintillation yield. The larger the yield, the larger the dynamic range, so a high-yield ISD would generate precise values even if the detector were positioned far away from the BT source. Furthermore, the impact of the stem signal would decrease as the scintillation yield increases. A large yield could also make it feasible to manufacture smaller detector probes with smaller detector volumes, thereby allowing for dosimeter probe placement in narrow catheters and causing a smaller perturbation in the dose field.

Real-time *in vivo* dosimetry during BT requires a time resolution on the order of 1 s but less than 3 s, so that timely error detections can be made (Andersen *et al* 2009, Kertzscher *et al* 2011b, 2014a) and so that dose rate changes caused by new BT source dwell positions can be monitored accurately. The dosimetry system we used in these experiments, which consisted of the ruby ISD, the 15 m PMMA cable, and the CCD camera setup, generated a ~2% statistical uncertainty in 1 s measurements for BT source positions 5 cm away from the detector volume. A statistical uncertainty of 1% could be achieved if the ruby ISD signal strength were 4 times higher; higher signal strength would improve the dose measurement precision during BT and increase error detection sensitivity. In contrast, the statistical uncertainty for 1 s measurements with the 1 mm long BCF-12- and BCF-60-based detectors was > 5%, showing that such small PSDs have limited capability to detect treatment errors during BT.

The simplest method to suppress the stem signal would be to introduce a band-pass filter between the fiber-optic cable and the photodetector system that transmits the wavelengths near the peak of the ruby emission spectrum. This method would exploit the separation of the narrow ruby emission spectrum, which is concentrated at longer wavelengths, from the stem signal spectrum that dominates at shorter wavelengths (see figure 3). However, the stem signal is not entirely negligible at longer wavelengths and can not be entirely eliminated with a band-pass filter. Our study showed that the stem signal converged to a minimum value as the width of the band-pass filter decreased. A 20 nm band-pass filter resulted in a near-minimum stem signal and a substantial ruby scintillation signal. The most significant stem signal was obtained for the half-sphere ruby-based ISD, for which the stem signal contribution was > 2% when the BT source dwelled 0.5 cm away from the PMMA fiber-optic cable and > 5 cm away from the detector volume. Such large stem signals would generate large dose measurement inaccuracies which would require increased measurement uncertainties and limited error detection sensitivity during BT.

Since the stem signal contribution is equal to the ratio between itself and the total detector signal (ruby radioluminescence, ruby photoluminescence, and stem signal), it is important to keep in mind that a sufficiently large ruby scintillation yield can reduce the significance of the stem signal background to negligible levels. For instance, as shown in figure 5, the stem signal accounted for up to 4% of the total signal. If the radioluminescence yield were ~6 or 3 times larger than the crystals used in this study, and if the photoluminescence yield were unchanged, the stem signal would be < 1% or < 2% of the total signal, respectively. Using a band-pass filter to suppress the stem signal, a combination of a ruby ISD with a 2 m PMMA fiber-optic cable and a high-scintillation-yield ruby crystal could minimize the stem signal to < 1%.

The unwanted ruby photoluminescence induced by the stem signal can, as shown in figure 5, enhance the total signal by > 5% for BT source positions 0.5 cm away from the fiber-optic cable and 7 cm away from the detector volume. Such a source-to-detector orientation is relevant for *in vivo* dosimetry, for instance, in a scenario where the ISD probe is inserted in the urethra and the detector volume placed near the bladder wall. Given the significance of the photoluminescence, it is therefore crucial to manufacture ruby-based ISDs that incorporate an optic filter between the scintillator and the fiber-optic cable to suppress the contribution of the ruby photoluminescence signal to insignificant values of around 1%. The photoluminescence suppression filter is particularly vital for ruby-based ISDs because photoluminescence is inherent to ruby, and could be even more significant than in the ruby crystals used in this study since the photoluminescence yield depends on the Cr^{3+} concentration in the Al_2O_3 crystal lattice (Toyoda *et al* 1998).

The optic filter sandwiched between the ruby crystal and the fiber-optic cable was made of polycarbonate, which exhibits discoloration due to electron beam irradiation (Faltermeier *et al* 2012). Extended exposure to the BT source can potentially discolor the polycarbonate-based optic filter, which may alter the transmission efficiency and also the photoluminescence suppression. The radiation hardness of the transmission efficiency of the optic filter needs to be further studied regardless of its material, e.g. polyester (available

from Rosco Laboratories Inc., USA), glass, or dye-mixed glue (see section 3.2), to understand the long term characteristics of the ruby ISD.

The fluorescence decay times of the ${}^2E \rightarrow {}^4A_2$ transitions are on the order of 1 ms or 10 ms, depending on the Cr^{3+} doping concentration and ambient temperature (Powell and DiBartolo 1972, Bessonova *et al* 1977). Using external beam radiotherapy sources, Jordan (Jordan 1996) measured a ~3 ms half-time, and Teichmann *et al.* (Teichmann *et al* 2013) measured 2 half-times of 2.54 ± 0.03 ms and 46.6 ± 0.6 ms. However, both our measurements and the results of Teichmann *et al.* (Teichmann *et al* 2013) demonstrate that some ruby crystals possess luminescence mechanisms with decay kinetics on the order of seconds (for example, Ruby #2 in figures 6 and 7), while others do not (Ruby #1 in figures 6 and 7). Bessonova *et al.* (Bessonova *et al* 1979) measured a significant ruby radioluminescence intensity buildup during constant dose rate exposure for ruby specimens that contained no specially introduced impurities. However, the buildup was absent if 0.5 wt. % vanadium was introduced in the ruby crystal. Bessonova *et al.* hypothesized that the introduction of Ti^{3+} , V^{3+} , and Mn^{3+} ions prevents the mechanism responsible for the radioluminescence buildup. Since undetected impurities can be introduced during the growth of the crystal, depending on the heat treatment used (Imbusch 1967, Bessonova *et al* 1979), and since the manufacturer listed Ti and Mn among the main impurities of the ruby crystals we used, the observed difference in time-dependent luminescence between Ruby #1 and Ruby #2 may be explained by the fact that the ruby crystals used in this study did not contain the same admixture of impurities.

The time-dependent luminescence mechanisms (afterglow and non-constant scintillation; see Sections 2 and 3.4) altered the monitored ruby ISD signal substantially and, therefore, also altered the measured dose rate, which in an *in vivo* dosimetry scenario could generate false alarms. As shown in section 3.4, the emission spectrum of the afterglow is nearly identical to that induced by radiation, so the time-dependent mechanisms cannot be filtered out. The only way to avoid this problem is, therefore, to ensure, prior to manufacturing the *in vivo* probe detector, that the ruby crystal used in the ISD probe does not exhibit significant time-dependent luminescence.

The following recommendations are made to improve the precision and accuracy of ruby-based ISDs for *in vivo* dosimetry during HDR BT:

- Ruby ISD signal strength enhancement:
The signal strength can be increased by a factor of ~4 by shortening the PMMA fiber-optic cable from 15 m to 2 m. Reflective paint on the ruby crystal can increase the signal strength by a factor of close to 3. Measurements by Bessonova *et al.* (Bessonova *et al* 1977) showed that the radioluminescence could vary up to a factor of ~3 depending on the Cr^{3+} ion concentration. Ruby crystals with optimized concentration of Cr^{3+} may therefore enhance the signal strength.
- Ruby photoluminescence suppression:

Since photoluminescence is inherent to ruby crystals, and since photoabsorption is dependent on the Cr^{3+} ion concentration (Toyoda *et al* 1998), it is crucial to incorporate a method to suppress it. The unwanted ruby photoluminescence signal was suppressed to < 1% of the total signal by introducing an optic filter between the fiber-optic cable and the ruby crystal.

- Stem signal suppression:

The filtering technique provides adequate stem signal suppression if proper measures to enhance the ruby ISD signal strength are incorporated. Since the emission spectrum of the ruby crystal is narrow, and since the ruby signal is attenuated more than shorter wavelengths, the stem signal contribution is less significant when the wavelength region of the band-pass filter is 20 nm around the ruby emission peak. Although the chromatic removal technique developed by Fontbonne *et al*. (Fontbonne *et al* 2002) is well established (Frelin *et al* 2005, Therriault-Proulx *et al* 2011a, Kertzscher *et al* 2011a), its application here would increase the complexity of the data acquisition system. It is the conviction of the authors that the simplicity of the data acquisition system is of high priority, since simplicity promotes cost efficiency, which in turn may lead to increased dissemination of *in vivo* dosimetry technology to BT clinics internationally. Therefore, the goal is to adapt the optic filtering technique in one optical channel.

- Time-dependent luminescence properties:

It is essential to ensure that the ruby crystal used does not exhibit afterglow or non-constant scintillation.

Before commissioning a ruby-based ISD for *in vivo* dosimetry, it will be important to characterize the energy and temperature dependence and to properly incorporate correction factors in the readout algorithm. It will also be potentially important to characterize the temperature dependence for each individual ruby crystal, since the rate of radioluminescence variation with temperature depends on the Cr^{3+} ion concentration (Bessonova *et al* 1977).

In conclusion, ruby-based ISDs are promising candidates for *in vivo* dosimetry during ^{192}Ir HDR BT. However, significant pitfalls related to their luminescence properties may compromise the dose measurement precision and accuracy and therefore need to be accounted for using solutions like those presented in this study. The signal strength of ruby-based ISDs are improved by shortening the length of the PMMA fiber-optic cable to < 5 m and by coating the surface of the ruby crystal with reflective paint. The signal strength of ruby ISDs is ~20 times larger than that of BCF-12 based detectors, assuming nearly no attenuation in the PMMA fiber-optic cable, and ruby ISDs produce insignificant statistical uncertainties for real-time *in vivo* dosimetry. The unwanted ruby photoluminescence signal can be suppressed to negligible levels by placing an optic filter between the fiber-optic cable and the ruby crystal. The stem signal can be suppressed adequately by introducing a narrow optic band-pass filter (< 20 nm) in the optical channel, providing that proper measures to

enhance the ruby ISD signal strength are incorporated. Depending on the admixture of impurities in the ruby crystal, time-dependent luminescence properties can generate measurement inaccuracies that severely impair the dose measurement accuracy. Therefore, as a precaution, ruby crystals that exhibit significant non-constant scintillation and inconsistent afterglow should be avoided.

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Figure 1.

The 3 types of detector probe tips that were used in the experiments: unfiltered with no reflective paint (left column), unfiltered with reflective paint (middle and right columns, top row), and filtered with reflective paint (middle and right columns, bottom row). All probe types were produced in multiples of 3.

Figure 2.

(a) The experimental setup used to measure the contributions of the radioluminescence, the stem signal, and the photoluminescence (ruby-based ISD only) to the total detector signal. The fiber-optic cables for configurations 1 and 2 are represented in the figure with different colors to better distinguishing them from each other. (b) The experimental setup to characterize the time-dependent luminescence properties of the ruby-based ISDs.

Figure 3.

The left-hand plot shows emission spectra of the detectors induced by the ^{192}Ir BT source for the detector probes used in this study. In addition to emission spectra, the right-hand plot shows the measured transmission efficiency of the optic filter that was placed between the scintillator and the fiber-optic cable of the filtered ruby-based ISDs.

Figure 4.

Top: The measured signal strengths for all 24 detectors used in the study. Bottom: The signal strengths of each BCF-60- and ruby-based detector normalized to the average value of the 3 BCF-12-based detectors. The signal strengths were corrected for the detector volume, the quantum efficiency (QE) of the charge-coupled device camera, and the attenuation of the poly(methyl methacrylate) fiber-optic cable. For each attenuation length, the ruby- and BCF-60-based detectors were normalized to BCF-12.

Figure 5.

The components of the total ruby ISD signal for ^{192}Ir BT source positions 0.5 cm away from the axis of the ruby ISD, assuming no attenuation in the PMMA fiber-optic cable. The top row represents the stacked, or superpositioned, signal components when the BT source was positioned 5 cm away from the ruby crystal along the fiber-optic cable. The bottom row represents the contributions of the signal components when the BT source was positioned 0 to 8 cm away from the ruby crystal along the fiber-optic cable. The signal contributions were calculated for wavelengths between 687 and 707 nm (indicated by the dashed vertical lines on the top row).

Figure 6.

The temporally non-constant scintillation of all 18 ruby-based ISDs during ~50 Gy irradiation with an ^{192}Ir BT source. Ruby #1 had weak time dependence, and Ruby #2 had strong time dependence. The light-blue dashed frame on the right-hand plot is a zoomed-in area indicated by the light-blue dashed frame on the left-hand plot.

Figure 7.

The afterglow of all 18 ruby-based ISDs after irradiation with an ^{192}Ir BT source. Ruby #1 had shorter half-times ($T_{1/2}$) than Ruby #2. The left inset (linear scale) shows that the wavelength spectrum of the afterglow of Ruby #2 was nearly identical to that of the radioluminescence (“irradiation”). The right inset (log-linear scale) indicates that the afterglow half-times for Ruby #2 were on the order of 1 and 10 seconds. The light-blue dashed frame on the right-hand plot is a zoomed-in portion of the area indicated by the light-blue dashed frame on the left-hand plot.

Table 1

Physical characteristics of the scintillator materials used in the study.

Scintillator material	Emission peak ^a (nm)	Density ^b (g/cm ³)	Index of refraction ^b (n _d)	Electron density ^c (electrons/cm ³)	Effective atomic number ^d (Z _{eff})	Shape	Volume (mm ³)
BCF-12 (organic)	435	1.05	1.60	3.4 × 10 ²³	5.7	Cylinder	0.79
BCF-60 (organic)	530	1.05	1.60	3.4 × 10 ²³	5.7	Cylinder	0.79
Ruby (inorganic)	694	3.98	1.77	1.2 × 10 ²⁴	11.3	Sphere Half-sphere	0.52 0.26

^aThe wavelength values of the emission spectra maxima were provided by the manufacturer for BCF-12 and BCF-60 and obtained from (Levine and Subramanian 1966) for ruby.

^bDensity and index of refraction were provided by manufacturers.

^cThe electron density values for BCF-12 and BCF-60 were provided by the manufacturer.

^dThe effective atomic number of polystyrene was used for BCF-12 and BCF-60 since it is the base of the scintillator material.

Table 2

Percent difference in the ruby ISD radioluminescence signal at different times (5, 10, 50, 100, and 200 s) with respect to the signal strength 1 s after the start of irradiation with an ^{192}Ir BT source. Signal strengths and percent values are listed for 2 ruby ISDs: Ruby #1, with a weakly time-dependent radioluminescence signal, and Ruby #2, with a strongly time-dependent signal.

Time after treatment start	Signal strength ^a	
	Ruby #1	Ruby #2
Baseline: 1 s (0.12 Gy)	1.4×10^5	7.5×10^5
5 s (0.6 Gy)	+ 0.9 %	+ 6 %
10 s (1.2 Gy)	+ 1.4 %	+ 9 %
50 s (6 Gy)	+ 1.7 %	+ 14 %
100 s (12 Gy)	+ 1.7 %	+ 16 %
200 s (24 Gy)	+ 1.9 %	+ 18 %

^aThe percentage values correspond to changes from the baseline values.