Inorganic scintillator detectors for real-time verification during brachytherapy

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Abstract
Widespread use of real-time dose measurement technology to verify brachytherapy (BT) treatments is currently limited because only few detectors exhibit the large dynamic range and signal intensities that is required to accurately report the data. Inorganic scintillator detectors (ISDs) are promising for real-time BT verification because they can exhibit large signal intensities. Luminescence properties of ISDs based on ruby, Y2O3:Eu and CsI:Tl were compared with BCF-60 plastic scintillators to determine their potential for BT verification. Measurements revealed that ISDs can exhibit signal intensities 1800 times larger than BCF-60 and that the Čerenkov and fluorescence light contamination is negligible. The favourable luminescence properties of ISDs opens the possibility to manufacture simplified detector systems that can lead to more widespread real-time verification during BT treatment deliveries.

1. Introduction
The dosimetric and clinical conditions in BT prevent the widespread use of scintillator detectors for in vivo dosimetry (IVD) [1,2]. The absorbed dose rate can shift by 2 orders of magnitude, e.g. if the BT source moves away from the detector from 0.5 to 5 cm, which requires the detector to be sensitive in a wide dynamic range. Furthermore, IVD in the tumor region requires insertion of the detector into narrow BT catheters which is possible only if the cross-section of the scintillator volume is small; preferably < 1 mm. However, small scintillator volumes limit the signal intensity and can lead to large statistical uncertainties which reduces the error detection capacity [1,3].

Inorganic scintillator detectors (ISDs) are promising for real-time IVD during BT because several materials exhibit light yields (photons/keV) ~1 order of magnitude greater than organic scintillators [4]. ISDs with large signal intensities may lead to small scintillator volumes that are sensitive in a wide dynamic range and that measure dose rates with small statistical uncertainties. Large signal intensities also reduce the impact of the stem signal, which is the contaminating Čerenkov and fluorescence light induced in the fiber-optic cable [5]. The stem signal is prominent for BT source positions near the fiber-optic cable and far from the scintillator volume, and requires complexity in the read-out system to suppress it for plastic scintillator detectors (PSDs) [6] because their signal intensity is limited [7,8].

The objective of this study was to assess the potential of ISDs for real-time verification during BT by comparing the signal intensity of inorganic scintillator materials with an organic scintillator that is commonly used in radiotherapy, and by evaluating the relevance of the stem signal contribution.
2. Material and methods

2.1. Detector systems

The ISDs and PSD consisted of a 1 mm-size scintillator that was optically coupled to a 1 mm-diameter and 15 m-long fiber-optic cable (ESKA GH-4001, Mitsubishi Rayon Co. Ltd., Japan) made of poly(methyl methacrylate) (PMMA). The fiber-optic cable transmitted the scintillation light to the photodetector system which consisted of a charge-coupled device (CCD) camera or a spectrometer spectrograph (Luca S 658M and Shamrock SR-163i, respectively, Andor Technology Ltd., UK).

The ISDs (see table 1) were based on a ruby crystal (Al₂O₃ doped with Cr³⁺; 49558, Edmund Optics Inc., USA), Y₂O₃:Eu in powder form (QK63/N-C1, Phosphor Technology Ltd, England) or CsI:Tl (SICCAS, Shanghai, China). The PSD was based on the organic scintillator BCF-60 (Saint-Gobain Crystals, France) which is made of polystyrene. The BCF-60, ruby and CsI:Tl volumes were coupled to the fiber-optic cable with transparent glue (NOA68, Norland Products Inc., USA) that was cured with ultraviolet light. The Y₂O₃:Eu volume was prepared by mixing 2 mass units Y₂O₃:Eu powder with 1 mass unit of the transparent glue. The mix was cured with ultraviolet light inside a transparent 1 mm-inner diameter plastic tubing attached to the fiber-optic cable.

| Scintillator material | Emission peak [nm] | Density [g/cm³] | Electron density [electrons/cm³] | Effective atomic number [Z eff] | Shape     | Volume [mm³] |
|----------------------|--------------------|----------------|-------------------------------|-------------------------------|-----------|--------------|
| BCF-60 (O)           | 530                | 1.05           | 3.4×10²³                      | 5.7                           | Cylinder  | 0.79         |
| Ruby (I)             | 694                | 3.98           | 1.2×10²⁴                      | 11.3                          | Half-sphere | 0.26         |
| Y₂O₃:Eu (I)          | 611                | 5.0            | 1.4×10²⁴                      | 36.1                          | Cylinder  | 0.79b        |
| CsI:Tl (I)           | 550                | 4.51           | 1.1×10²⁴                      | 54.0                          | Cube      | 1.0          |

a. One organic (O) and 3 inorganic (I) scintillator materials were included in this study.
b. The volume of the Y₂O₃:Eu crystals inside the 0.79 mm³ cylinder-shaped scintillator was ~0.26 mm³.

The scintillator volume of the ISDs were covered with a reflecting material to enhance the signal intensity. The ruby and Y₂O₃:Eu volumes were covered with reflective paint (EJ-510, Eljen Technology, USA) and the CsI:Tl crystals enclosed by manufacturers with polytetrafluoroethylene. The influence of the photoluminescence (PL) of the ISDs was suppressed by placing a thin plastic optic filter (Rosco Laboratories Inc., USA) between the scintillator volume and the fiber-optic cable (adapted from [9]).

2.2. Measurements

A Nucletron MicroSelectron v2 HDR afterloader was used throughout all experiments, and the air-kerma strength of the ¹⁹²Ir source was between 17.6 and 29.4 mGy m² h⁻¹.

2.2.1. Scintillation intensities. The relative signal intensities of the ISDs and PSD were determined based on measurements of 3 different detector samples of each scintillator material. The signal intensity of the bare fiber without a scintillator volume was subtracted from the ISD and PSD intensities to remove the influence of the stem signal. The signal intensities were measured individually for each detector placed 2 cm from the BT source in a rigid polymer-based phantom (Solid Water, Gammex, USA). The scintillation intensities and electronic noise were recorded per unit time with the CCD camera setup, which incorporated a 25-mm (F1.8) lens (Computar, USA) and a 25-mm spacer. The total measurement variability due to the positional uncertainty of the detectors and BT source, repeated connections between the detectors and CCD camera, and statistical uncertainty was < 5%. The measurements were corrected for differences in scintillator volumes, the quantum efficiency of the CCD camera, and the attenuation in the PMMA fiber-optic cable.

2.2.2. Stem signal. The stem signal contamination for the ISDs and PSD was determined based on scintillation intensity and emission spectra measurements, and on absorbed dose calculations [10]. The signal intensities of the detectors and the bare fiber were measured under identical BT source irradiation.
conditions, for which the absorbed dose in the scintillator volume and fiber-optic cable were calculated. The signal intensity per absorbed dose was obtained for each scintillator material and the fiber-optic cable by dividing the measured intensities with the calculated absorbed doses.

The emission spectra of the scintillator materials and the stem signal were measured with the spectrometer. The emission spectra were normalized to the corresponding signal intensity per absorbed dose value, such that each wavelength bin value was proportional to the absorbed dose in the scintillator volume or the fiber-optic cable. The emission spectra and the signal intensities were corrected for the attenuation in the PMMA fiber-optic cable and the quantum efficiency (QE) of the photodetectors.

The normalized emission spectra were multiplied by calculated absorbed doses in the scintillator volume and fiber-optic cable corresponding to various BT source positions relative to the detectors. The calculations allowed determining the stem signal contamination for the ISDs and PSD, e.g. for BT source positions near the fiber-optic cable and far from the scintillator volume.

3. Results and Discussion

Emission spectra of the scintillator materials and the PMMA fiber-optic cable that were induced by an $^{192}$Ir BT source are shown in figure 1 (left-hand plot). The spectra have been corrected for the quantum efficiency of the spectrometer and the attenuation in 15 m PMMA fiber-optic cable.

The measurements revealed higher signal intensities for all ISDs compared with the BCF-60-based PSD (figure 1, right-hand log-scale plot). The signal intensity of the ruby-based ISD was 16 times larger than that of the PSD for 15 m PMMA attenuation and 39 times larger for 0 m attenuation. The corresponding values for the $Y_2O_3:Eu$-based ISD were 63 and 92, and 1700 and 1800 for the CsI:Tl-based ISD. The wavelength-dependence of the attenuation in PMMA governs the signal increase when the fiber-optic cable is shortened. If shortened from 15 to 0 m, the signal intensities would increase by a factor 1.5, 3.7, 2.2, and 1.6 for the BCF-60-, ruby-, $Y_2O_3:Eu$-, and CsI:Tl-based detectors, respectively.

![Figure 1](image)

**Figure 1.** (Left) Emission spectra induced by an $^{192}$Ir BT source of the scintillators used in this study and of the PMMA fiber-optic cable. (Right) Measured and corrected scintillation intensities of the detectors. The ISD intensities were normalized to the average value of the 3 BCF-60-based PSDs. The intensities were corrected for the size of the detector volume, the quantum efficiency (QE) of the CCD camera, and the attenuation in the fiber-optic cable.

The signal components for each detector for BT source positions 1 cm from the axis defined by the fiber-optic cable are shown in figure 2. The coordinate-convention defined for the TG-43 protocol is assumed [10]. The ISDs incorporated a long-pass filter between the scintillator and the fiber to suppress the PL background. The left-hand plot shows the superposition of the scintillation and stem signal for each detector when the source is placed 1 cm from the fiber-optic cable and 5 cm from the scintillator. The right-hand plots show that the stem signal is prominent for BCF-60-based PSDs and less prominent for the ISDs. The stem signal is ~3% of the total signal for ruby-based ISDs when the
BT source is 8 cm away from the scintillator, and 0.7% and 0.2% for the Y$_2$O$_3$:Eu- and CsI:Tl-based ISDs, respectively.

**Figure 2.** (Left) The sum of the scintillator and stem signal (PMMA) for each scintillator material used in this study. The emission spectra are proportional to the signal intensities when an $^{192}$Ir BT source is placed 1 cm from the fiber-optic cable and 5 cm from the scintillator volume. (Right) The contribution of the different signal components in the PSD and the 3 ISDs for BT source positions 1 cm from the axis defined by the fiber-optic cable.

### 4. Conclusion

Inorganic scintillator detectors (ISDs) based on ruby, Y$_2$O$_3$:Eu and CsI:Tl are strong candidates for real-time verification for brachytherapy (BT), primarily because of their large signal intensities that were up to 39, 92 and 1800 times larger, respectively, than that of BCF-60-based plastic scintillator detectors. The stem signal is negligible for CsI:Tl-based ISDs, which establishes that complexity in the read-out system to suppress it can be avoided. Correction methods for the temperature- and energy-dependence of the ISD response are necessary. ISDs can open new frontiers for simplified, cost effective detector systems that can lead to more widespread real-time verification during BT.

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