Technical Note: Removing the stem effect when performing Ir-192 HDR brachytherapy *in vivo* dosimetry using plastic scintillation detectors: A relevant and necessary step

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Purpose: The purpose of this study was to investigate whether or not a stem effect removal technique is necessary when performing Ir-192 HDR brachytherapy *in vivo* dosimetry using a scintillation detector.

Methods: A red-green-blue photodiode connected to a multichannel electrometer was used to detect the light emitted from a plastic scintillation detector (PSD) during irradiation with an Ir-192 HDR brachytherapy source. Accuracy in dose measurement was compared with and without the use of stem effect removal techniques. Monochromatic and polychromatic filtration techniques were studied. An in-house template was built for accurate positioning of catheters in which the source and the PSD were inserted. Dose distribution was measured up to 5 cm from source to detector in the radial and longitudinal directions.

Results: The authors found the stem effect to be particularly important when the source was close to the optical fiber guide and far from the scintillation component of the detector. It can account for up to $(72 \pm 3)\%$ of the signal under clinically relevant conditions. The polychromatic filtration outperformed the monochromatic filtration as well as the absence of filtration in regard to dose measurement accuracy.

Conclusions: It is necessary to implement a stem effect removal technique when building a PSD for *in vivo* dosimetry during Ir-192 HDR brachytherapy. The PSD that the authors have developed for this study would be suitable for such an application. © 2011 American Association of Physicists in Medicine. [DOI: [10.1118/1.3562902](https://doi.org/10.1118/1.3562902)]

Key words: stem effect, Cerenkov, plastic scintillation detectors, *in vivo* dosimetry, HDR

I. INTRODUCTION

There is an increased interest in performing real-time *in vivo* dosimetry during Ir-192 high dose rate (HDR) brachytherapy.¹⁻⁹ The small size, near water equivalence, energy independence (>100 keV), dose linearity, dose rate independence, fast response, and temperature independence¹⁰⁻¹² make plastic scintillation detectors (PSDs) an attractive choice for this purpose. Advantages of PSDs were demonstrated extensively for megavoltage external beams¹⁰⁻¹³ and it is well known for high energy beams that it is necessary to remove the stem effect light: The light induced by radiation in the optical fiber guiding the scintillation light toward the photodetector.¹⁴⁻¹⁸

For Ir-192 HDR brachytherapy, the need for a stem effect removal technique is not so obvious. Previous studies^{4,9} revealed that it is not necessary to implement a stem effect

removal technique when building PSDs for *in vivo* dosimetry during Ir-192 HDR brachytherapy. However, most of the energy spectrum of an Ir-192 source is above the threshold for Cerenkov. Cerenkov radiation is emitted in a material whenever a charged particle passes through a medium with a velocity higher than that of light in that medium. In the case of polymethyl methacrylate (PMMA), the material that comprises many optical fibers, the Cerenkov threshold corresponds to an energy of about 178 keV. The photon energy spectrum for Ir-192 is between 0.136 and 1.06 MeV with an average energy of 380 keV, leading to the expectation of a substantial production of Cerenkov radiation in the optical fiber light guide of the PSD. Andersen *et al.*¹⁹ reported results supporting the latter statement, showing situations where the stem effect account for up to 30% of the total signal when irradiating an Al₂O₃ scintillator coupled to a

FIG. 1. Experimental setup and positioning template system (embedded). Catheters were connected to transfer tubes, which were connected to the afterloader. The PSD (with the black jacket on the picture) was connected to the RGB photodiode outside the treatment room.

PMMA fiber with an Ir-192 source used for pulsed dose rate (PDR) brachytherapy.

The purpose of our study was to investigate whether or not a stem effect removal technique is necessary when performing Ir-192 HDR brachytherapy *in vivo* dosimetry using a PSD. The PSDs we developed allowed for the implementation of monochromatic and polychromatic stem effect removal techniques. Comparison between dose measurements obtained with these different techniques as well as without any stem effect removal technique was performed.

II. MATERIALS AND METHODS

A Nucletron HDR Ir-192 brachytherapy system (Nucletron B.V., Veenendaal, The Netherlands) was used for all measurements conducted in this study. Irradiation was delivered using a microSelectron V2 Ir-192 afterloader, with a source of 0.90 mm in diameter and 4.95 mm in length connected to a stainless steel cable. Source was traveling inside plastic catheters inserted in an in-house developed positioning template placed inside a water tank (see Fig. 1). A PSD was also inserted inside a catheter reserved for dosimetry purposes. The detection volume of the PSD was composed of a 1 mm diameter $\times$ 2 mm long BCF-60 green scintillating fiber (Saint-Gobain Crystals and Detectors, Paris, France). The scintillating fiber was coupled to a light tight 8 m long $\times$ 1 mm diameter PMMA optical fiber (Eska Premier GH-4001, Mitsubishi Rayon Co., Ltd., Tokyo, Japan), which was then coupled to a photodetector outside the treatment room. The photodetector used in this study was a red-green-blue (RGB) photodiode (Mazet MCSiAT). To prevent electric perturbation from the environment as well as light leakage, the photodiode was enclosed in an aluminum box connected to the ground. Two of the three color outputs from the RGB photodiode were used throughout the experiments—the blue and the green—in order to allow for the implementation of both the monochromatic and the polychromatic stem effect removal techniques. The photodiode outputs were triax connected to a double input channel electrometer (SuperMax, Standard Imaging, Madison, WI) with a computer controlling the electrometer and collecting data from it via an RS-232 cable.

TABLE I. Dose calculation for the different stem effect removal approaches. In this study, M_1 corresponds to the charge recorded from the green output and M_2 corresponds to the charge from the blue output.

Method	Dose equations
No filtration	$D = a(M_1 + M_2)$ (1)
Monochromatic filtration	$D = aM_1$ (2)
Polychromatic filtration	$D = aM_1 + bM_2$ (3)

Different stem effect removal approaches were compared in this study. Table I shows the dose equation proper to each technique. The approach without any filtration technique was mimicked by the summation of the blue and green outputs. The monochromatic filtration technique was first introduced by de Boer *et al.*¹⁶ and was used by Andersen *et al.* in their study.¹⁹ This technique confines the acquired light to a specific spectral band: The one in which the scintillation light is dominant (in this study, the green one), thus ensuring an increase in signal to stem effect ratio. The polychromatic technique was first introduced by Fontbonne *et al.*¹³ and is now extensively used for higher energy dosimetry.^{18,20–22} It is based on the assumption that light emission spectra from scintillation and stem effect light are different. It then uses the light signals collected in two different spectral bands to obtain, following a proper calibration, the dose deposited at the PSD's position.

In order to calibrate the PSD for the different techniques, measurements were performed in two known-dose irradiation conditions. The first two methods depicted in Table I require only one known-dose calibration point as there is only one calibration factor to determine. In contrast, the polychromatic approach requires at least two known-dose conditions to solve for the two unknown calibration factors in the equation. Using the Monte Carlo (MC) calculated data from Daskalov *et al.*²³—computed for the same Ir-192 source model—for the dose at the point of measurement, calibration factors were obtained following the equations in Table I.

The efficiency of each technique to remove the stem effect and lead to accurate dosimetry was investigated. Definition of the z axis is presented at the bottom of Fig. 2, where the active component of the PSD is located at $z=0$ cm. r is simply the radial distance from the center of the cylindrical scintillating component. In order to decrease the source-to-scintillator positioning uncertainty in the z axis and ensure an accurate comparison of measured to expected values, we matched the dose distributions along the z axis obtained from measurement with the MC data from Daskalov *et al.*²³ The positioning uncertainty in the z direction was evaluated to be 0.4 mm. The use of the template allowed achieving a positioning uncertainty of 0.2 mm along the radial axis. The experiment consisted of measuring dose using the PSD at different source-to-scintillator positions. Dose delivery catheters were placed at radial distances (r) of 0.5, 1.0, 3.0, and 5.0 cm from the catheter where the PSD was inserted. The source was moved in each catheter for z positions ranging from -5.0 to 5.0 cm by 0.5 cm steps. The dose was then

FIG. 2. Relative difference (in %) of the doses obtained using the different stem effect removal approaches to the expected dose as a function of z for $r=0.5, 1.0, 3.0$, and 5.0 cm. Error bars were calculated from addition in quadrature between the standard deviation of measurements and the effect on dose from positioning accuracy.

calculated for each source-to-scintillator position with each of the three different approaches and compared to the expected values from Daskalov *et al.*²³ Five measurements were taken for each position. The mean and standard deviation were calculated. The standard deviation is a combination, in quadrature, of the measurements uncertainty and the effect on dose comparison from the uncertainty in positioning.

III. RESULTS

Dose measurements were performed for each source positions described above. The relative differences to the expected values are shown in Fig. 2 with their uncertainty for the different radial positions ($r=0.5, 1.0, 3.0$, and 5.0 cm). Only positive z positions are presented in Fig. 2 for clarity purposes. As it was expected, when the source was far from the optical fiber guide ($z < 0$), the results were consistent among the techniques and with the reference data within measurements uncertainty. We can see in Fig. 2 that the stem effect is particularly important when the source is close to the fiber and far from the scintillator. The polychromatic filtration technique was shown to outperform both the no filtration and the monochromatic techniques. In the highest stem effect contribution condition ($r=0.5$ cm, $z=5.0$ cm), the relative difference to the expected value was equal to $(72 \pm 3)\%$ for no filtration, $(41 \pm 3)\%$ with the monochromatic filtration, and $(-12 \pm 8)\%$ with the polychromatic tech-

nique. According to our results and associated error bars, the need for stem effect correction is not as necessary for radial positions greater than 3 cm.

IV. DISCUSSION AND CONCLUSION

Our study showed that it is necessary to implement a stem effect removal technique in order to perform accurate *in vivo* dosimetry during Ir-192 HDR brachytherapy treatments. The polychromatic filtration technique yielded the best results. The use of a second color channel (blue) allowed for the subtraction of the stem effect component from the signal of interest beside than a simple optimization of the scintillation to stem effect ratio as it is in the case for the monochromatic technique. The necessity for a stem effect removal technique under certain irradiation conditions is supported by the results from Andersen *et al.*¹⁹ using a different type of scintillation detector. Using an Al_2O_3 radioluminescence/optically stimulated luminescence detector for *in vivo* dosimetry under a Ir-192 PDR brachytherapy source, they reported up to a 30% influence from the stem effect on the signal and concluded that it was relevant to account for the stem effect component. Their study was already implementing a monochromatic filtration technique in their detector. That result is in good agreement with our measured worst-case difference of $(41 \pm 3)\%$ when using the monochromatic filtration technique.

As stated before, another group of researchers stated that it was not necessary to account for the stem effect to achieve accurate *in vivo* dosimetry using PSDs during Ir-192 HDR brachytherapy.^{4,9} The results from Cartwright *et al.*⁹ look at first sight in contradiction with what we showed here. They reported an average stem effect contribution of 3% at $r=3.5$ cm with a 4 mm scintillator and no filtration technique was implemented in their study. However, they reported a dependence of the stem effect with the radial source-to-detector distance of $1/r^{0.83}$, which would then lead to an average stem effect contribution of 15.1% for a radial distance of 0.5 cm. The average value of the data we obtained without filtration at $r=0.5$ cm was about a 27% difference to the expected values attributed to the stem effect. As the scintillator we used in our study was half the length of the one used by Cartwright *et al.* (2 mm vs 4 mm), we would expect the stem effect contribution in our study being higher. Thus, once compared on a similar footing, all the results seem to converge toward significant stem effect for conditions explored in this work. However, because of the particularly large source-to-scintillator radial positions $r=3.5$ cm selected by Cartwright *et al.* to state their conclusion, the clinical importance of stem effect removal could be misleading.

When considering the different possible source-to-scintillator positions, we showed that it is necessary to implement a stem effect removal technique when building a PSD for dosimetry during Ir-192 HDR brachytherapy, especially for dwell positions close to the optical fiber ($r < 3$ cm) and far from the scintillating component ($z > +3$ cm). Such conditions are seen on regular basis in most brachytherapy applications. Even if there exist some source-

to-scintillator positions where the stem effect could be neglected, taking into account the stem effect should ensure a better versatility of the detector and should prevent possible measurement errors when performing Ir-192 HDR brachytherapy dose verification using scintillation detectors. In light of our results, the PSD we developed together with the polychromatic filtration technique would be suitable for Ir-192 HDR brachytherapy dosimetry applications.

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