Study of the response of plastic scintillation detectors in small-field 6 MV photon beams by Monte Carlo simulations

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Purpose: To investigate the response of plastic scintillation detectors (PSDs) in a 6 MV photon beam of various field sizes using Monte Carlo simulations.

Methods: Three PSDs were simulated: A BC-400 and a BCF-12, each attached to a plastic-core optical fiber, and a BC-400 attached to an air-core optical fiber. PSD response was calculated as the detector dose per unit water dose for field sizes ranging from 10×10 down to 0.5×0.5 cm² for both *perpendicular* and *parallel* orientations of the detectors to an incident beam. Similar calculations were performed for a CC01 compact chamber. The off-axis dose profiles were calculated in the 0.5×0.5 cm² photon beam and were compared to the dose profile calculated for the CC01 chamber and that calculated in water without any detector. The angular dependence of the PSDs' responses in a small photon beam was studied.

Results: In the perpendicular orientation, the response of the BCF-12 PSD varied by only 0.5% as the field size decreased from 10×10 to 0.5×0.5 cm², while the response of BC-400 PSD attached to a plastic-core fiber varied by more than 3% at the smallest field size because of its longer sensitive region. In the parallel orientation, the response of both PSDs attached to a plastic-core fiber varied by less than 0.4% for the same range of field sizes. For the PSD attached to an air-core fiber, the response varied, at most, by 2% for both orientations.

Conclusions: The responses of all the PSDs investigated in this work can have a variation of only 1%–2% irrespective of field size and orientation of the detector if the length of the sensitive region is not more than 2 mm long and the optical fiber stems are prevented from pointing directly to the incident source. © 2011 American Association of Physicists in Medicine.

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I. INTRODUCTION

Plastic scintillation detectors (PSDs) have many advantages over other types of radiation detectors, including their excellent water equivalency, high spatial resolution, photon beam-quality independence, dose rate independence, linearity with dose, and instantaneous readout.^{1,2} The major drawback of PSD-based dosimetry systems is their generation of Čerenkov light in the optical fiber guide that is attached to the PSD when the optical fiber is exposed to a radiation field.³ Fortunately, the problem of Čerenkov light in PSDs can be resolved either by removing the Čerenkov light from the PSD's signal^{4–6} or by preventing its production in the first place with the use of an air-core optical fiber.^{7,8} Recently developed radiation therapy modalities, such as intensity-modulated radiation therapy and stereotactic radiosurgery, are characterized by small field sizes that require reliable dosimetry methods.^{9–11} Although some ionization chambers (PinPoint, CC01, etc.) are especially designed for small-field photon beam dosimetry, their spatial resolution (roughly 1–2 mm) is still inadequate for very small field sizes (i.e., 0.5×0.5 cm²). PSDs have been used for small-field photon beam dosimetry^{12–15} and applied in real-time *in vivo* dosimetry.¹⁶ In this study, Monte Carlo simulation method is

used to investigate the field size dependence of the response of PSDs in a 6 MV photon beam.

II. MATERIALS AND METHODS

The EGSnrc Monte Carlo code system¹⁷ is employed for the simulations of three PSDs in a 6 MV photon beam throughout this study. This photon energy is chosen because the majority of clinical photon beams of small field come from IMRT and stereotactic radiosurgery which usually have a nominal energy of 6 MV. Two of the PSDs simulated in this study are attached by a plastic-core (PMMA) optical fiber. The simulated PSDs were based on the specifications of the commonly used BC-400 and BCF-12 PSDs (Saint-Gobain Crystals, Nemours, France); the plastic-core optical fiber was modeled after the Eska Premier GH4001 (Mitsubishi Rayon Co., Ltd., Tokyo, Japan). The third simulated PSD is a BC-400 PSD attached by an air-core optical fiber. The geometrical design and material details of this PSD can be found from published studies.^{7,8} An optical fiber stem of 3 cm length was used for all the simulated PSDs in the simulations. The detailed data and/or schematic drawings for these PSDs can be found in our previous study.¹⁸ A CC01 compact chamber (IBA Dosimetry GmbH, Schwarzenbruck, Germany) is also simulated here for comparison. The detec-

tors (PSDs or chamber) were simulated as if they were positioned at a depth of 10 cm in a cubic water phantom. The photon beam is a point source at a 100 cm source-to-surface distance of energy 6 MV, whose spectrum was taken from a Monte Carlo simulation of a Varian linac.¹⁹ Each detector's response was calculated as the ratio of the dose in the detector's sensitive region to the dose at the point of measurement in the water without the detector. For water dose calculations, the scoring voxel is cylindrically shaped and it is oriented with the end faces perpendicular to the incident beam. All the detectors were simulated using the C++ user code Cavity of the EGSnrc code system.²⁰

Like a Farmer-type chamber, a PSD is typically placed at depth in a phantom with its axis of symmetry perpendicular to the incident beam. However, for very small field sizes, e.g., 0.5×0.5 cm², the length of the detector's sensitive region (0.2–0.4 cm) is comparable to the field size. Since the diameter of the sensitive region of all the detectors studied here is smaller than the length of the sensitive region, these detectors are usually rotated by 90° to improve their spatial resolution when they are used in a small field. Thus, two orientations of the PSDs (also for the CC01 chamber) are studied when positioning the detectors with its geometrical center of the sensitive region at the point of measurement: (1) The detector was positioned with its axis *perpendicular* or *normal* to the incident beam and (2) the detector was positioned with its axis *parallel* to the incident beam and with its head pointing to the radiation source. First, the field size dependence of the detectors' responses was calculated for both orientations for field sizes of 10, 6, 3, 2, 1, and 0.5 cm (field size of 0.6 cm also studied for some of the detectors). For the water dose calculations, the lateral voxel size (diameter) was varied from 10 to 0.4 mm to ensure a uniform lateral dose distribution within the voxel while maximizing the calculation efficiency. For the smallest field size (0.5×0.5 cm²), the off-axis dose profiles were calculated from the PSDs and the CC01 chamber simulations, as well as the profile in water only. In the dose profile calculations, all detectors were positioned in the parallel orientation and were displaced by various distances from the central axis. For the water-only calculations, one had to be careful that the dose in a voxel is sensitive to the lateral size of the voxel at the penumbral region where the dose gradient is high. To ensure that the correct dose value is obtained, the water dose was calculated for a voxel with different lateral sizes at a location 2.5 mm from the central axis where the dose gradient is close to highest. It is found that the water dose value stabilized when the voxel radius was less than 0.24 mm. Thus, a voxel radius of 0.2 mm was used for all the water dose profile calculations for the 0.5×0.5 cm² field. Finally, the angular dependence of all the PSDs and two bare polystyrene PSDs was calculated in the 0.5×0.5 cm² photon beam. The two bare PSDs have the same diameter of 1 mm but with different lengths of 2 and 4 mm, corresponding to the size of the sensitive regions of the BCF-12 and BC-400 PSDs. They are studied here to see how much proportion of the angular dependence of PSDs comes from the sensitive region itself,

FIG. 1. Field size dependence of the responses of (a) the three PSDs and (b) the CC01 compact chamber, simulated in both the normal and parallel orientations at a 10 cm depth in a water phantom in a 6 MV photon beam. The response was defined as detector dose per unit water dose.

which would be the intrinsic angular dependence of the PSDs.

Calculations are also done for the response of all the simulated PSDs for both the orientations at a depth of 1.5 cm (i.e., depth of maximum dose for the 6 MV beam) in the 0.5×0.5 cm² field. The results show that the discrepancy at the two depths (1.5 and 10 cm) is, at most, 0.6% for parallel orientation and 0.3% for perpendicular orientation, with calculation uncertainty of less than 0.1%. One topic not addressed in this study is the output factors, which are important characteristics for small field beams and they can be measured for various field sizes.¹⁴ This is because any such studies require a detailed, validated linac head model which is not available to us due to the lack of the geometrical and material data for the various linac head components.

III. RESULTS AND DISCUSSION

The field size dependence of the PSD responses is shown in Fig. 1(a). For the parallel orientation, the responses of the BCF-12 and BC-400 PSDs attached to a plastic-core optical fiber varied by less than 0.4% as field size decreased from 10×10 to 0.5×0.5 cm². In the same orientation, however, the BC-400 PSD attached to an air-core fiber over-responded by 2% in the smallest field (0.5×0.5 cm²). The reason for this over-response is that the silica around the sensitive region has a greater influence on detector response for small fields than for large fields since the scattering contribution is diminished in small fields. In other words, when the field size becomes smaller, the dose in the PSD drops slower than

the dose in water because the high-Z material (Si) around the sensitive region of the PSD becomes relatively more important and thus results in a higher dose ratio. For the perpendicular orientation, the response of the BCF-12 PSD varied by only 0.5% for the same range of field sizes, while the response of the BC-400 PSD attached to a plastic-core fiber varied by $\sim 3.5\%$ in the smallest field because of its longer sensitive region (4 mm). In contrast, the response of the BC-400 PSD attached to an air-core fiber, which also has a longer sensitive region than the BCF-12 PSD, varied by only 1.5% as field size decreased from 10×10 to 0.5×0.5 cm². The reason for this 2% reduction in response variation between the BC-400 PSDs attached to air-core and plastic-core fibers is the same as that given above for the 2% over-response of the PSD with air-core fiber in the parallel orientation. For field sizes down to 0.5×0.5 cm², there were variations in the responses of these PSDs. The major cause of the variation is the length of the sensitive region of the PSD, which is comparable to the field size when the PSD is placed with its axis perpendicular to the incident beam. A length of 2 mm for the sensitive region results in an excellent field size independence down to 0.5×0.5 cm². One may expect that a shorter length has a better field size independence and spatial resolution, but a too-short length may not be practically feasible because of the corresponding too-low signal level. So a length of 2–4 mm is commonly used for PSDs. Figure 1(b) shows the field size dependence of the CC01 ion chamber responses for the two orientations. Not surprisingly, even for the parallel orientation, the detector response varied by 2.5% as the field size decreased from 10×10 to 0.5×0.5 cm²; for the perpendicular orientation, it varied by more than 5% for the same range of field sizes. The ion chamber's larger sensitive volume or air cavity accounts for these large variations in response.

The off-axis dose profiles in the 0.5×0.5 cm² photon beam from the detector simulations and water-only calculations are shown in Fig. 2. As shown, the calculated dose profiles for the three simulated PSDs were very close to that of water, except at the steep gradient region (2.5–3 mm). However, the dose profile from the CC01 chamber simulation was clearly different from those of the PSD simulations because of the volume averaging effect for the chamber's relatively large sensitive volume.

The angular dependences of the three PSDs in the small-field (0.5×0.5 cm²) photon beam are shown in Fig. 3. For angles from 90° to 180° , i.e., the PSD's head was proximal to the source, the variations in responses for the BCF-12 PSD, the BC-400 PSD with a plastic-core fiber, and the BC-400 PSD with an air-core fiber were 1.4%, 4.6%, and 4.1%, respectively. For angles from 0° to 90° , the variations in responses for the three PSDs were as large as 3.6%, 5.0%, and 2.5%, respectively. These values are higher than those obtained for the same radiation source and at the same depth in the water phantom with a large (10×10 cm²) field size.¹⁸ This is mainly because the field size here is so small and comparable to the size of the PSD's sensitive region. Figure 3 also shows the angular dependence of two bare polystyrene

FIG. 2. Off-axis dose profiles calculated in water and from the detector simulations at a depth of 10 cm in a water phantom in a 6 MV photon beam with a field size of 0.5×0.5 cm² and at a source-to-surface distance of 100 cm. Both the PSDs and the CC01 chamber were placed with their axis parallel to the beam direction. The relative response here is defined as the ratio of dose at an off-axis position to dose at the central axis.

PSDs, which correspond to the size of the sensitive regions of the BCF-12 and BC-400 PSDs. Note that, in fact, the sensitive material for the BC-400 PSD is polyvinyltoluene (PVT); nonetheless, after calculating the angular dependence of a bare PVT (data not shown), it agreed within 0.1% to that of the bare polystyrene. From Fig. 3, one may conclude that the angular dependence of the PSDs in the angle range 90° – 180° in the small-field photon beam is solely determined by the size of their sensitive region. However, when the tail of the PSDs is pointing toward the source, the response of the PSDs was complicated, suggesting that the optical fiber perturbs the dose response markedly for this small field. The

FIG. 3. Angular dependence of the three simulated PSDs and two bare PSDs made of polystyrene at a 10 cm depth in a water phantom in a 6 MV photon beam with a field size of 0.5×0.5 cm². Angles are defined as shown in the inset. The detector dose at any angle was normalized to that at 90° and this defines the relative response. The length of the optical fiber stem was simulated as being 3 cm.

response of BC-400 with plastic-core fiber matches that of the bare PSD of the same sensitive region; however, this might be coincidental since there is a significant difference in response between the BCF-12 and the corresponding bare PSD. For the BC-400 PSD with an air-core fiber, the response at 0° was 2.5% lower than that of the BC-400 PSD with a plastic-core fiber. This was likely due to the combined effects of silica and air, which resulted in an additional attenuation of the primary photons in the sensitive region of the detector; this result is also consistent with our previous results for a large field.¹⁸

IV. CONCLUSIONS

The responses of PSDs in small-field 6 MV photon beams were investigated by Monte Carlo simulations. The detectors' responses were calculated as the ratio of the dose in the detector's sensitive volume to the dose at the same point in water. Three PSD models were simulated in this study: A BC-400 and a BCF-12, both attached to a plastic-core fiber, and a BC-400 attached to an air-core fiber. For the photon beams of different field sizes, the response of all the simulated PSDs was found essentially independent of field size at the 0.5% level or less for field sizes ranging from 10×10 to 1×1 cm², no matter whether they are oriented parallel or perpendicular to the source. At the smallest (0.5×0.5 cm²) field size and for parallel orientation, the 0.5% variation is still maintained for the PSDs with plastic-core fiber but it may over-respond by a couple of percent for the PSD with air-core fiber. The off-axis dose profiles obtained from all the PSD simulations in a 0.5×0.5 cm² field were almost the same as the dose profile calculated in water in the same field because of the PSD's close-to-water equivalency. The study of the angular dependence of the PSD response shows that a length of 2 mm is preferred to longer lengths for the scintillator's sensitive region in order to have a smaller angular dependence for very small field photon beams. These studies showed that the responses of all the PSDs investigated in this work can have a variation of only 1%–2% irrespective of field size and orientation of the detector, if the length of the sensitive region is not more than 2 mm long and the fiber stems are prevented from pointing to the incident source. That is, these PSDs are excellent dosimeters for small-field measurements and it is expected that they will find wide applications for IMRT QA, stereotactic radiotherapy and small field dosimetry.

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