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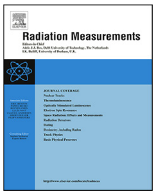

# Characterization of a fiber-taper charge-coupled device system for plastic scintillation dosimetry and comparison with the traditional lens system

Louis-Philippe Gagnon [a, b], Sam Beddar [c], Luc Beaulieu [a, b, *]

[a] Département de Physique, de Génie Physique et d'Optique and Centre de recherche sur le Cancer, Université Laval, Québec, Québec G1K 7P4, Canada
[b] Département de Radio-Oncologie et Centre de recherche du CHU de Québec, CHU de Québec, Québec G1R 2J6, Canada
[c] Department of Radiation Physics, Unit 94, The University of Texas MD Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, TX 77030, USA

## HIGHLIGHTS

- We compare a fiber-taper-based photon-counting system to a lens based system.
- We quantify the increase of photons collected on the CCD using fiber guiding.
- We study the systems SNR and accuracy increase offered by the taper system.
- Increased accuracy at low-dose measurements is achieved with the use of the taper.

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## ABSTRACT

*Purpose:* To compare the signal-to-noise ratio (SNR), dose sensitivity and stability, and reproducibility of a lens-less charge-coupled device (CCD) photon-counting system with those of a traditional CCD + lens photon-counting system for plastic scintillation detectors (PSDs).
*Methods:* The PSD used in this study was made from a 1-mm diameter, 2-mm long BCF60 scintillating fiber (emission peak at 530 nm) coupled to a 2.6-m Eska GH-4001 clear plastic fiber. This PSD was coupled to either a fiber-taper-based photon-counting system (FTS) or a lens-based photon-counting system (LS). In the FTS, the fiber-taper was attached to a $2048 \times 2048$ pixel, uncooled Alta 4020 polychromatic CCD camera. The LS consisted of a $1600 \times 1200$ pixel Alta 2020 polychromatic CCD camera (cooled to $-18\,^{\circ}$C) with a 50-mm lens with $f/\# = 1$. Dose measurements were made under the same conditions for each system (isocentric setup; depth of 1.5 cm in solid water using a $10 \times 10$ cm$^2$ field size and 6-MV photon beam). The performance of each system was determined and compared, using the chromatic Čerenkov removal method to account for the stem effects produced in the clear plastic fiber.
*Results:* The FTS increased the light collected by a factor of 4 compared with the LS, for the same dose measurements. This gain was possible because the FTS was not limited by the optical aberration that comes with a lens system. Despite a $45\,^{\circ}$C operating temperature difference between the systems, the SNR was 1.8–1.9 times higher in the FTS than in the LS, for blue and green channels respectively. Low-dose measurements of 1.0 and 0.5 cGy were obtained with an accuracy of 3.4% and 5.6%, respectively, in the FTS, compared with 5.8% and 15.9% in the LS. The FTS provided excellent dose measurement stability as a function of integration time, with at most a 1% difference at 5 cGy. Under the same conditions, the LS system produced a measurement difference between 2 and 3%.
*Conclusion:* Our results showed that the FTS could measure doses more accurately than the LS and that low-dose measurements were feasible without the complexity of a lens-based system. The FTS would therefore be better adapted for routine clinical usage of fiber arrays. The increased SNR in the FTS suggests that water-equivalent PSDs with smaller radii could be used to obtain measurements with

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* Corresponding author. Département de Physique, de Génie Physique et d'Optique, Centre de recherche sur le Cancer, Université Laval, Québec, Québec G1K 7P4, Canada.
*E-mail address:* beaulieu@phy.ulaval.ca (L. Beaulieu).

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greater spatial resolution, further simplifying the use of PSDs for “in-vivo” monitoring and small-field dosimetry.

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## 1. Introduction

As radiation therapy techniques have evolved to more specifically target tumors and spare normal tissues (e.g., intensity-modulated radiation therapy, volumetric modulated arc therapy) (Otto, 2008; Wolff et al, 2009; Bertelsen et al., 2010; Stein et al., 1994), more precise dosimeters are needed than the currently available ionization chambers, which were designed to be efficient in wide radiation fields (Laub and Wong, 2003; Das et al., 2008; Low et al., 2003; Leybovich et al., 2003). Plastic scintillation detectors (PSDs) have been proposed for use with these radiation therapy techniques as a means of improving spatial resolution and accuracy of the dose detected (Beddar et al., 1992a, 1992b, 2001; Fontbonne et al, 2002; Lambert et al., 2010; Andersen et al., 2011; Morin et al, 2013; Letourneau et al., 1999).

In Beddar et al.'s first description of scintillating dosimetry using plastic optical-fiber coupled to CCD detectors 20 years ago (Beddar et al., 1992a), the water-equivalence and linear response of PSDs in the entire radiotherapy energy range suggested that PSDs had great potential to be used without any correction factor for energy dependence or for the detector's material. Beddar et al. (1992b) also proposed a method to remove the Cerenkov stem effect from the signal and demonstrated that it was possible to make precise dose measurements using a PSD and a photomultiplier tube. Today, important advances have allowed the development of multidimensional scintillating dosimeters (Goulet et al., 2012; Gagnon et al, 2012; Lacroix et al., 2008; Guillot et al., 2011a).

Technological advances have also allowed the use of various techniques and devices to collect and separate the Cerenkov noise from the useful fluorescent light in PSDs; such devices include photodiodes (Letourneau et al., 1999; Therriault-Proulx et al., 2011), photomultiplier tubes (de Boer et al., 1993; Beddar et al., 2003), electron multiplying charge-coupled devices (EM-CCDs) (Lacroix et al., 2010; Cartwright et al., 2010), and CCD cameras (Lacroix et al., 2010; Frelin et al, 2005; Guillot et al., 2011b; Archambault et al., 2006). Liu et al. (1996) showed that among these detection devices, the use of the CCD camera gives the best results in regard to the quantum efficiency and the SNR. The current approach of using a CCD camera with a lens to collect light gives good results and is well adapted for 1D and 2D PSD arrays (Lacroix et al., 2008; Guillot et al., 2013) and for multiple elements in-vivo measurements (Archambault et al, 2010; Klein et al, 2012; Wootton et al., 2014), but the low collection efficiency of this approach limits the dynamic range and precision of the measurements to the sensible volume of the PSD used. Furthermore, the uncertain long-term stability of a lens system in a clinical setting, in which the device would be repeatedly moved around, constitutes a severe limitation of the CCD technology. To ensure stability and reproducibility of the results between different measurement sessions it is important to readjust the system's focus and the components' alignment, thus demanding a new calibration every time. This is suboptimal for regular clinical usage.

The purpose of this study was to build and characterize the performance of a lens-less CCD photon-counting system that uses a new optical guidance technique, a fiber-taper, to improve the collection efficiency of the PSD, while providing a simplified, robust set-up that does not need fine adjustment every time it is used. X-ray imaging systems using fiber tapers have been already studied and used efficiently in digital mammography and digital radiography (Liu et al., 1993; Maidment and Yaffe, 1996), so its use in a radiotherapy scintillating dosimetry device is expected to provide good results. This approach was previously described on a theoretical basis by Lacroix et al. (2010) and should have a coupling efficiency greater than the standard lens system. In this work, we compare the proposed taper system with a well-established CCD + lens photon-counting system in terms of signal-to-noise ratio (SNR), dose sensitivity and measurement stability.

## 2. Materials and methods

### 2.1. PSD assembly

All of the results presented in this study were obtained using the same PSD assembly, coupled to two different photon-counting systems (described below). This ensured that the comparison of the acquisition devices was not influenced by photon flux at the output of the collecting clear fiber. The PSD assembly was composed of a polished cylindrical scintillating fiber (BCF-60; Saint-Gobain Crystals, Paris, France; emission peak at 530 nm) with a diameter of 1.0 mm and a length of 2.0 mm, coupled to a 2.6-m long polished PMMA clear-optical fiber (Eska Premier GH-4001; Mitsubushi, Rayon Co., Ltd., Tokyo, Japan), following the method described by Ayotte et al. (2006) The whole device was protected from ambient light by a polyethylene sheath and its effective point of measurement was considered to be the geometric center of the scintillating volume (Lacroix et al, 2010).

#### 2.1.1. Fiber-taper-based photon-counting system

The first photon-counting device used a custom designed 3:1 fiber-taper to guide the input image to the sensitive area of the polychromatic CCD. The taper acts like a waveguide, reducing the magnitude of the images by a predetermined factor of 3:1. The fiber-taper used in the present study was made to fit the size of the photon-collecting area of the associated CCD camera. In this fiber-taper system (FTS), as shown in Fig. 1, the fiber-taper was directly attached to the sensitive area (a $2048 \times 2048$ pixel chip) of an uncooled Alta polychromatic CCD camera (U4020; Apogee Imaging System, Roseville, CA, USA). The standard Peltier cooling device of this camera was disabled to avoid damage to the electronics from condensation of the ambient humidity. Because this fiber-taper worked in total internal reflection instead of refraction, no specific focal length was required to get a sharp signal. The closer the detector was to the surface of the taper, the better the signal was to the CCD camera.

#### 2.1.2. Lens-based photon-counting system

The second optical system was a more traditional system that focused a light source to a CCD chip using an optical lens. The photon-counting system consisted of a $1600 \times 1200$ pixel Alta polychromatic CCD camera (U2020; Apogee Imaging System) cooled to $-18$ °C. This camera was coupled to a 50-mm focal length lens with $f/\# = 1.0$ (JML Optical Industries, Rochester, NY, USA). This lens system (LS) has the advantage that it may be cooled enough to greatly reduce readout and black noise, improving the stability and

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