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Development of a scintillating fiber-optic dosimeter for measuring the entrance surface dose in diagnostic radiology

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HIGHLIGHTS

► Fabrication of a scintillating fiber-optic dosimeter for use in diagnostic radiology.
► Measurements of the scintillating light according to the exposure parameters.
► Comparison of the entrance surface doses obtained using conventional dosimeters.

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ABSTRACT

As a direct method, a scintillating fiber-optic dosimeter (SFOD) was fabricated using an organic scintillator, a plastic optical fiber, and a photomultiplier tube (PMT) to measure entrance surface doses (ESDs) in diagnostic radiology. In this study, we measured the scintillating lights, which are altered by to the exposure parameters, such as the tube potential, current-time product, and focus-surface distance (FSD), with an SFOD placed on the top of an acrylic and aluminum chest phantom to provide a backscatter medium. The scintillating light signals of the SFOD were compared with the ESDs obtained using conventional dosimeters. The ESDs that were measured using the dose-area product (DAP) meter, as an indirect method, and a semiconductor dosimeter, as a direct method, were distinguished according to differences in the measurement position and the method used. In the case of the two direct methods with the SFOD and the semiconductor dosimeter, the output light signals of the SFOD were similar to the ESDs of the semiconductor dosimeter. It is expected that the SFOD will be a useful dosimeter for diagnostic radiology due to its many advantages, including its small size, lightweight, substantial flexibility, remote sensing, real-time monitoring, and immunity to electromagnetic interference (EMI).

1. Introduction

In diagnostic radiology, X-ray examinations should be conducted for limited medical purposes to minimize of unnecessary patient exposure. Furthermore, the patient dose should be carefully considered to determine the reference dose levels. The patient dose is generally described by the entrance surface dose (ESD), which is measured at the center of the X-ray beam.

Various procedures, such as the calculation method, indirect measurement, and direct measurement, have been developed to estimate the ESD in diagnostic radiology. First, the ESD can be calculated using basic parameters for the X-ray unit and set up. Although calculation methods are inexpensive and much easier than other methods, the X-ray tube and high voltage generator must be strictly controlled to achieve the desired accuracy. Calculation methods are continually being developed to more accurately assess the ESD. Second, the ESD can be measured indirectly using a dose-area product (DAP) meter (McParland, 1998; Bahreyni Toosi et al., 2004; Zoetelief et al., 2005). When a DAP meter is placed at the end of the collimator, it cannot provide an immediate measurement of the ESD, and mathematical equations are required to convert the measured DAP value into an ESD value. Finally, the ESD can also be measured directly using different types of dosimeters, including a thermo-luminescent dosimeter (TLD), a glass dosimeter, radiographic film, and an ionization chamber (George et al., 2004; Hyer et al., 2009). However, the aforementioned

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dosimeters, with the exception of the ionization chamber, cannot be used in real-time dosimetry because they require time-consuming reading processes after irradiation. The ionization chamber has a large sensitive volume for in-phantom measurements and requires a complicated correction process.

To overcome these problems, dosimeters based on scintillators and optical fibers have been developed for real-time dosimetry in radiation diagnosis (Hyer et al., 2009; Jones and Hintenlang, 2008; Benevides et al., 2007) and radiotherapeutic applications (Lee et al., 2010; Jang et al., 2009; Beddar, 2007; Beddar et al., 1992a,b; Beierholm et al., 2011). Generally, optical fiber-based radiation sensors have several advantages over conventional electrical sensors, including a small volume, long-distant signal transmission, good flexibility, and immunity to electromagnetic interference (EMI), because they use optical fibers to transmit light signals. Although fiber-optic radiation sensors have many advantages in radiotherapy that relies on high-energy therapeutic photons or electron beams, Cherenkov radiation can be generated by the direct action of the radiation in the transparent optical fiber, which is attached to the dosimeter probe of a fiber-optic radiation sensor. This can cause problems in the measurement of pure scintillating light signals (Law et al., 2007; Beddar et al., 1992c, 2004). In diagnostic applications, however, the effects of Cherenkov radiation are not a concern with the fiber-optic radiation sensor because Cherenkov radiation cannot be produced in an optical fiber under low-energy radiation beams (Hyer et al., 2009).

In this study, we fabricated a scintillating fiber-optic dosimeter (SFOD) using an organic scintillator for real-time and direct dosimetry during radiation diagnosis. The SFOD shows many desirable qualities, including real-time monitoring, remote sensing, small sensitivity volume, dose linearity and reproducibility.

2. Materials and methods

2.1. SFOD system

The proposed SFOD is composed of a dosimeter probe, a plastic optical fiber and a light-measuring device for measuring ESDs in diagnostic radiology. For the sensitive element of the dosimeter probe, we used three kinds of plastic scintillating fibers (BCF-10, 12, and 20, Saint-Gobain Ceramic & Plastics) whose physical properties are listed in Table 1 (Saint-Gobain Ceramic & Plastics, Inc., 2008). The plastic scintillating fiber has a cylindrical shape and a core/clad structure, similar to the general optical fiber, that has an outer diameter of 2.0 mm. The materials of the core and the cladding are polystyrene (PS $(C_8H_8)_n$) with a density of 1.05 g/cm^3 and polymethylmethacrylate (PMMA $(C_5H_8O_2)_n$) with a density of 1.2 g/cm^3, respectively, and the core is synthesized with PS and fluorescent dopants. The refractive indices of the core and cladding are 1.60 and 1.49, respectively, and the numerical aperture (NA) is 0.58. Before conducting the experimental study on the SFOD, three kinds of plastic scintillating fibers were tested to select an optimum organic scintillator that is suitable for use with a light-measuring device such as a photo-multiplier tube (PMT). As a result of our findings, we selected BCF-10 as the sensing material for the SFOD because it provided the highest light output in our experimental setup.

Table 1
Physical properties of the three kinds of plastic scintillating fibers.

Organic scintillator	Emission color	Emission peak (nm)	Decay time (ns)	1/*e* length (m)	# of photons per MeV
BCF-10	Blue	432	2.7	2.2	~8000
BCF-12	Blue	435	3.2	2.7	~8000
BCF-20	Green	492	2.7	>3.5	~8000

A plastic optical fiber (SH-6001, Mitsubishi Rayon) was used to guide scintillating light from the dosimeter probe of an SFOD to a light-measuring device. This optical fiber is multi-modal and has a step refractive index profile. The outer and core diameters are 1.50 ± 0.09 and 1.47 ± 0.09 mm, respectively. The refractive index of the core is 1.49, and the NA is 0.50. The core and cladding materials are PMMA resin and fluorinated polymer, respectively, and the jacket is composed of black polyethylene (PE). The maximum transmission loss of this optical fiber is 200 dB/km when used with 650 nm collimated light. The length of the plastic optical fiber used in this study is approximately 6 m, which is a sufficient distance to prevent noise in the light-measuring device due to incident or scattered radiation.

As a light-measuring device, a PMT module (H5784, Hamamatsu Photonics) with a measurable wavelength ranging from 300 to 650 nm and a peak sensitive wavelength of 420 nm was used. This photosensing system is composed of a metal package PMT equipped with an optical fiber adapter such as a subminiature type A (SMA) connector, a high voltage power supply, and a low-noise amplifier.

Figs. 1 and 2 show the structure of the dosimeter probe and a schematic diagram of the SFOD system, respectively. The plastic scintillating fiber, which has a length of 10.0 mm, was polished and connected to the distal end of the plastic optical fiber using a PMMA connector. To increase the scintillating light collection efficiency, the outside of the scintillator was coated with a titanium dioxide (TiO_2)-based reflective paint (BC-620, Saint-Gobain Ceramic & Plastics). Furthermore, the dosimeter probe was covered with black shielding tape to intercept the ambient light noise. The scintillating light generated by the interactions between the X-ray beam and the organic scintillator in the dosimeter probe, which was placed on the X-ray system in the examination room, was guided to the PMT in the control room via a 6 m plastic optical fiber and then converted to an electric signal. The output signal generated by the PMT was amplified by a low-noise amplifier and connected to a data acquisition (DAQ) board (NI USB-6259, National Instruments), and a laptop running LabVIEW (Version 8.6, National Instruments).

2.2. Experimental setup for the measurement of ESDs

Fig. 3 illustrates the experimental setup for measuring the ESDs with a DAP meter, semiconductor dosimeter, and SFOD. To compare the three dosimeters, the experiment was carried out using an

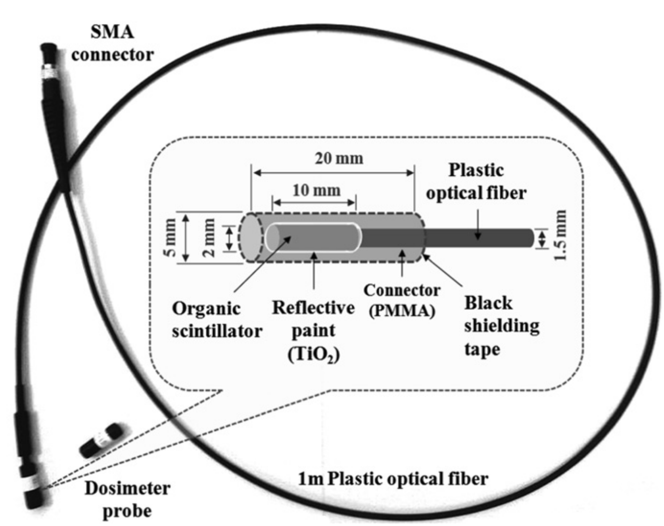

Fig. 1. Structure of a dosimeter probe of the SFOD.