Light scattering in optical CT scanning of Presage dosimeters

Y Xu, J Adamovics, J C Cheeseborough, K S Chao and C S Wuu

1 Department of Radiation Oncology, Columbia University, New York, NY 10032
2 Department of Chemistry, Rider University, Lawrenceville, NJ 08648
3 Department of Radiation Oncology, Weill Cornell Medical College, New York, NY 10065

E-mail: yx2010@columbia.edu

Abstract. The intensity of the scattered light from the Presage dosimeters was measured using a Thorlabs PM100D optical power meter (Thorlabs Inc, Newton, NJ) with an optical sensor of 1 mm diameter sensitive area. Five Presage dosimeters were made as cylinders of 15.2 cm, 10 cm, 4 cm diameters and irradiated with 6 MV photons using a Varian Clinac 2100EX. Each dosimeter was put into the scanning tank of an OCTOPUS™ optical CT scanner (MGS Research Inc, Madison, CT) filled with a refractive index matching liquid. A laser diode was positioned at one side of the water tank to generate a stationary laser beam of 0.8 mm width. On the other side of the tank, an in-house manufactured positioning system was used to move the optical sensor in the direction perpendicular to the outgoing laser beam from the dosimeters at an increment of 1 mm. The amount of scattered photons was found to be more than 1% of the primary light signal within 2 mm from the laser beam but decreases sharply with increasing off-axis distance. The intensity of the scattered light increases with increasing light attenuations and/or absorptions in the dosimeters. The scattered light at the same off-axis distance was weaker for dosimeters of larger diameters and for larger detector-to-dosimeter distances. Methods for minimizing the effect of the light scattering in different types of optical CT scanners are discussed.

1. Introduction

Gel dosimeter is a promising 3D dose verification system that could have wide applications in routine clinical radiation therapy practice. Among the imaging methods studied for gel dosimetry so far, optical CT is the only approach that utilizes equipments designed for gel dosimeters with expected accuracy and spatial resolution. The advantage of the optical CT approach over other dose readout methods for gel dosimetry is commonly acknowledged [1-2]. It has been postulated that gel dosimetry using a bench-top optical CT scanner will be a valuable tool for patient-specific treatment dose verification, periodic quality assurance of radiation therapy units, and commissioning of new treatment techniques and machines.

In optical CT scanning of 3D dosimeters, the dose distribution recorded in a dosimeter is represented by the 3D optical density map caused by the light attenuation and/or absorption from the radiation induced micro-particles in the dosimeter. Therefore, only the portion of the incoming laser beam that survives the multiple Rayleigh-Mie scattering and/or light absorption in the forward direction should be used for image reconstruction [3-4]. Artifacts caused by the scattered light in different optical CT scanners were reported and discussed previously [5-8].

The purpose of this study is to give a quantitative estimation of the intensity of the scattered light in regions where light signals might be collected for image reconstruction in optical CT-based 3D dosimetry. Even though the measurements were done for the Presage dosimeters inside the scanning tank
of an OCTOPUS™ research CT scanner, the results can be used as a general guideline to minimize the effect of light scattering in the design and operation of different optical CT scanners.

2. Materials and methods

The Presage dosimeters used in this study are one cylinder of 4 cm diameter, one cylinder of 10 cm diameter, and three cylinders of 15.2 cm diameter (see Fig. 1a). All the dosimeters were irradiated with 40 cm x 40 cm, 6 MV photon fields using a Varian 21EX linear accelerator. Before the irradiations, the background optical density drop (OD) across each dosimeter was measured and the monitor units for irradiating the dosimeters were estimated according to the following criteria:

1. The optical density drops across the three dosimeters of 15.2 cm diameter should vary substantially in the range from 0 to 4.

2. The optical density value for one of the 15.2 cm diameter dosimeter should be comparable to those for the dosimeters of 4 cm and 10 cm diameters.

![Figure 1: Materials used in this study: a) Presage dosimeters of 4 cm, 10 cm, and 15.2 cm diameters; b) laser beam, water tank, and the in-house manufactured positioning system.](image)

The irradiated dosimeters were put on the turntable of an OCTOPUS™ optical CT scanner filled with a refractive index matching liquid. A laser diode was put on one side of the scanning tank to generate a stationary laser beam of 0.8 mm diameter and 633 nm wavelength. The position of each dosimeter in the tank was adjusted such that the laser beam passed through the central region of the dosimeter. The outgoing laser signal from the tank was recorded by a Thorlabs optical power meter with an optical sensor of 1 mm diameter sensitive area. The operating frequency of the power meter was set to be 635 nm. An in-house manufactured positioning system was used to move the optical sensor to the off-axis positions from -9 cm to 9 cm at an increment of 1 mm (Fig. 1b). The light signal at each off-axis position was recorded and the ratio to the intensity of the primary beam at the central position was taken.

Prior to the measurements on the irradiated dosimeters, the intensity of the light signal at each position for the tank filled with the refractive index matching liquid was recorded. All the 6 sets of measurements were done with a detector-to-tank distance of 2 cm. In order to study the dependence of the intensity of the scattered light on the detector-to-tank distance, the measurements were also repeated for one of the 15.2 diameter dosimeters with a detector-to-tank distance of 10 cm.
3. Results

Figure 2 shows the intensity of the light signal measured for the tank fill with the refractive index matching liquid only. The power of the outgoing laser beam from the tank was determined to be 1.532 milliwatts. For the ±1 mm off-axis positions, the primary laser beam was partially detected by the optical sensor and the recorded laser signal was significant. For off-axis distance $\geq 2$ mm, the intensity of the scattered light was less than 1% of the primary laser intensity and dropped sharply with increasing off-axis distances.

Figure 2: Distribution of the measured light intensity for the scanning tank filled with the refractive matching liquid.

Figure 3 compares the distributions of the intensity of the light signal for the three dosimeters of 15.2 cm diameter. The optical density drops across the dosimeters (defined as the logarithm of the ratio of 1.532 mw to the laser intensity at the central position) were 0.247, 1.9 and 3.32 respectively. It can be seen that the intensity of the scattered light increases with increasing light attenuation and absorption within the dosimeter. For the two dosimeters with optical density values of less than 2, the intensities of the scattered photons at more than 3 mm off-axis distances are all less than 1% of the primary beam. For the dosimeter with optical density value of 3.32, however, the intensity of the scattered light was more than 3% of the primary laser beam even for off-axis distance of 5 mm. Furthermore, the drop of the intensity of the scattered light at larger off-axis distances is slower for dosimeter of large optical density values. For the dosimeter of 3.32 optical density, the intensity of the scattered light is more than 1% of the primary laser beam even at the 9 cm off-axis position. It should be pointed out that the 3.32 optical density is beyond the valid dynamic ranges for most of the optical CT scanners [11].

Figure 3: Comparison of the light intensity distributions for the three Presage dosimeters with 15.2 cm diameter and 0.247, 1.9 and 3.32 optical density values (OD).

Figure 4 compares the distribution of the intensity of the light signal from the dosimeter of 15.2 cm diameter with those from the dosimeters of 10 cm and 4 cm diameters. The optical density drops across the three dosimeters were 1.9, 1.83, and 1.79, respectively. For dosimeters of comparable optical density values, the intensity of the scattered light was found to decrease with increasing dosimeter diameter.

Figure 5 shows the results for the dosimeter of 15.2 cm diameter and 1.9 optical density value taken at two detector-to-tank distances (2 cm and 10 cm). The intensity of the scattered light at the same off-axis distance is weaker for larger detector-to-tank distances.
4. Discussion

Minimizing the effect of light scattering has been an important consideration in the design and operation of optical CT scanners. Currently, there are two groups of optical CT scanners: one is based on a single laser source coupled to a single photodiode detector and the other uses incoherent broad light source and a large area detector such as a CCD camera. The methods for handling the scattered photons in these two groups of scanners are different.

The basis for separating the scattered light from the real signal has to do with the angular distribution of the scattered photons. As is shown in Figs. 3, 4 and 5, the majority of the scattered photons are distributed within a small angle from the direction of the scanning beam inside the dosimeters. For scanners using a single laser source and a small area detector, OCTOPUS™ scanner, for example, the photodiode detector does not have to be positioned to face the scanning laser beam. Instead, the point laser source can be guided through a series of reflective mirrors (and/or lenses) to scan across the dosimeters and reach the photodiode detector. Collection of the scattered light at the detector aperture is therefore limited to photons going through multiple scattering only. Furthermore, with fine tuning of the optics and the refractive index matching, the position of the primary laser beam on the detector surface can be adjusted to be stable during the entire scanning process. The detector aperture can be reduced to a few millimeters such that the collection of the scattered photons by the detector is minimal.

When the detector has to be placed to face the light source, as is the case for the CCD camera approach, the effect of the scattered photons can be minimized in a variety of ways [9-10]. For instance, a telecentric lens can be placed in front of the CCD camera to ensure that only the incoming parallel light rays in certain directions are collected by the camera. However, considering the dimension of the camera lens, collection of the scattered photons within a small angle from the direction of the parallel light rays is inevitable. Furthermore, the scattered photons are mostly distributed in a small angle from the primary laser beam, as is shown in the present study.

An alternative for reducing the effect of light scattering is to decrease the overall optical density drop across the dosimeters scanned, at the price of a diminished overall signal-to-noise ratio. As is shown in Fig. 3, smaller attenuation of the scanning laser beam within a dosimeter can result in smaller amount of scattered photons everywhere. For dosimeters with optical density values of less than 2, the intensity of the scattered light at the position of 2 mm off-axis distance is less than 1.5%. A balance between the
experimental uncertainties generated by the light scattering and other type of noises might be necessary in some cases.

5. Conclusions
We have performed a preliminary study on the effect of light scattering in optical CT scanning using the Presage dosimeters, the water tank of the OCTOPUS™ optical CT scanner, and an in-house manufactured light intensity measuring system. The intensity of the scattering light from the Presage dosimeters was found to decrease with increasing off-axis distance from the primary laser beam and increasing detector-to-dosimeter distance. The amount of the scattered photons was demonstrated to be smaller for dosimeters with less attenuation of the primary laser beam. For dosimeters of the same optical density value, the intensity of the scattered light is larger for smaller dosimeter diameters.

6. References
[1] Baldock C, De Deene Y, Doran S, Ibott G, Jirasek A, Lepage M, McAuley K B, Oldham M and Schreiner L J 2010 Polymer gel dosimetry Phys. Med. Biol. 55, R1-R63.
[2] Oldham M, Siewerdsen J H, Shetty A S and Jaffray D A 2001 High resolution gel-dosimetry by optical-CT and MR scanning Med. Phys. 28 1436-44.
[3] Gore J C, Ranade M, Maryanski M J and Schulz R J 1996 Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: I. Development of an optical scanner Phys. Med. Biol. 41, 2695-2704.
[4] Maryanski M J, Zastavker Y Z, and Gore J C 1996 Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: II. Optical properties of the BANG polymer gel Phys. Med. Biol. 41, 2705-17.
[5] Islam K T S, Dempsey J F, Ranade M, Maryanski M J and Low D A 2003 Initial evaluation of commercial optical CT-based 3D gel dosimeter Med. Phys. 30, 2159-68.
[6] Xu Y, Wuu C S and Maryanski M J 2003 Determining optimal gel sensitivity in optical CT scanning of polymer gels Med. Phys. 30, 2257-63.
[7] Doran S J, Koerkamp K K, Bero M A, Jenneson P, Morton E J and Gilboy W B 2001 A CCD-based optical CT scanner for high-resolution 3D imaging of radiation dose distributions: equipment specifications, optical simulations and preliminary results Phys. Med. Biol. 46, 3191-3213.
[8] DeJean P, Senden R, McAuley K B, Rogers M and Schreiner L J 2006 Initial experience with a commercial cone beam optical CT unit for polymer gel dosimetry II: Clinical potential Journal of Physics: Conference Series 56 183–6.
[9] Krstajić N and Doran S J 2006 Focusing optics of a parallel beam CCD optical tomography apparatus for 3D radiation gel dosimetry Phys. Med. Biol. 51, 2055-75.
[10] Sakhalkar H S and Oldham M 2008 High-resolution 3D dosimetry utilizing a novel optical-CT scanner incorporating tertiary telecentric collimation Med. Phys. 35, 101-111
[11] Xu Y, Wuu C S and Maryanski M J 2004 Performance of optical CT scanning of polymer gels as a tool for 3D dose verification Med. Phys. 31 3024-30.