Development of CCD-based optical computed tomography and comparison with single-beam optical CT scanner

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Abstract. This study reports on the development of CCD-based optical computed tomography (CT) CT-s2. A commercially available 10× fast optical computed tomography scanner (OCTOPUSTM-10X, MGS Research, Inc., Madison, CT, USA) was used for comparison. NIPAM polymer gel dosimeter was used to validate the performance of CT-s2. The gamma pass rate can reach 96.00% when using a 3% dose difference and 3 mm dose-to-agreement criteria. The results of CT-s2 are as good as those of the single-beam optical-CT scanner, but the scanning time of CT-s2 is only one-tenth of that of the single-beam optical-CT scanner.

1. Introduction
As a readout tool, optical computed tomography (optical CT) is superior to MRI owing to such advantages as low-cost, high-speed scanning time, and high resolution [1]. The introduction of the radiochromic plastic dosimeter has also gained considerable attraction in the field of optical CT. Many geometries of the optical CT scanner have been revealed in the application of gel dosimetry [2]. The first-generation single-beam optical CT scanner was developed by Gore et al [3]. The IMRT measurement result obtained by using the first-generation single-beam optical CT is still considered as the gold standard in the field [4-6]. However, this technology is hindered by long scanning time. To reduce the scanning time, the fast single-beam optical CT (OCTOPUS™-10× optical CT scanner, MGS Research Inc., Madison, CT) based on rotating mirror and Fresnel lens was revealed by MGS to be 10 times faster than the first-generation optical CT scanner [7, 8]. Another fast imaging modality utilizes a diffuser and CCD to acquire a complete 2D projection image at each rotating angle, tremendously reducing the scanning time to approximately several minutes [9-12]. However, some challenges associated with the use of CCD-based optical CT have to be addressed. These challenges include spatial uniformity of light source, FOV size, scattering artifacts, low-noise CCD, and best-fit matching liquid [9].

Although many geometries of CCD-based optical CT have been presented previously, stable, low-cost, high accuracy, high precision and fast optical-CT was rarely reported. Based on the NIPAM gel, on which our research group has conducted detailed investigation [14-16], this study uses prior knowledge on optical CT to implement an improved CCD-based parallel beam optical CT (CT-s2). This device is based on a specially designed positioning mechanism involving a uniform light plane that uses a spatial filter, a microscope objective lens, a pinhole and one rotating diffuser, two large-
diameter lenses, and an automated acquisition system. Regarding to the NIPAM gel dosimeter, the scanning result of CT-s2 is comparable with that by OCTOPUS\textsuperscript{TM}-10×.

2. Materials and Methods

Figure 1 shows a photograph of the CT-s2 optical CT scanner implemented in this study. CT-s2 includes a solid-state laser (120 mW power and 660 nm wavelength, Power Technology Inc., Little Rock, AR, USA), spatial filter, a microscope objective lens (40X), pinhole (diameter 5 μm), rotating diffuser, two collimating lenses, and a CCD (1296 pixels × 966 pixels, scA1300-32fm, BASLER AG, Ahrensburg, Germany). The laser was used because it can generate a uniform light source combined with a spatial filter and pinhole. The gel container with 10 cm diameter and 10 cm height is fixed on a rotating plate in an aquarium with dimensions of 32 cm × 32 cm × 32 cm. The rotating plate is mounted on a stepper motor fixed under the aquarium. All components are mounted on a stable anti-vibration optical table (Newport Corporation, Irvine, CA, USA). An in-house control program written by Labview (NI Inc.) rotates the gel phantom while capturing the image. The rotating speed is 1 degree per second, and 360 images are acquired at 360 degrees. The gel phantom filled with NIPAM [5% gelatin (300 Bloom Type A, Sigma-Aldrich), 5% NIPAM (97% pure; Sigma–Aldrich), 3% N, N’-methylene bisacrylamide (Bis), and 5 mM Tetrakis (hydroxymethyl phosphonium chloride) was prepared and placed in an acrylic phantom. The gel phantom was irradiated using a 6 MV Varian Clinac IX linear accelerator (Varian Corporation, Palo Alto, CA, USA). The treatment plan consists of five fields of IMRT irradiation with gantries aligned at 120°, 155°, 180°, 215°, and 245°. The maximum prescribed dose is 6.8 Gy at the central region.

After irradiation, the gel phantom was scanned by the CT-s2 and OCTOPUS\textsuperscript{TM}-10× optical CT scanner. The preparation process was based on the steps outlined in previous research [13-15]. The matching liquid was 1.346 following the best fit RI of NIPAM [16].

3. Results and discussion

3.1. Projection images and sinogram

Before acquiring an image, optical alignment was carefully conducted to ensure a uniform light field. Repeated adjustment is required to achieve a high-quality light plane. The uniformity is 7.8% \(((\text{maximum grey value-minimum grey value})/ (\text{mean grey value})/2\) for the central 10 cm × 10 cm region of the FOV. Figure 2 shows the projection image and sinogram of non-irradiated gel phantom acquired by the CCD camera, whereas figure 3 shows the projection image and sinogram of irradiated gel phantom acquired by the CCD camera.
3.2. Reconstruction

After acquiring 360 projections, an inverse-radon transform algorithm was implemented in MATLAB (The Math-Works, Inc.) to reconstruct the image. Figure 4 illustrates the reconstruction images of the CT-s2 (upper row) and OCTOPUS™-10× (lower row) optical CT scanner. The gel phantoms are the same for both scanners but the FOV is different because the design of both scanner is different. The image processing technique used for the results in this study is wiener2, a 2D noise-removal filtering function built in MATLAB.
3.3. Gamma evaluation
A quantitative evaluation method was adopted in this study. The gamma evaluation technique [17] compares the measured and reference doses by using composite of dose-difference and distance-to-agreement (DTA) comparison criteria. The TPS image shown in figure 4 was used as reference for gamma passing rate calculations for both CT-s2 and OCTOPUS™-10× optical CT scanner. The criteria are 3% dose-difference and 3 mm DTA. The pass rate is 96.00% and 95.13% for CT-s2 and OCTOPUS™-10× optical CT scanner, respectively.

4. Conclusion
This study showed that a CCD-based parallel optical CT used as gel dosimeter readout tool performs as well as a single-beam optical CT. Better optical alignment, best fit matching liquid, and mechanical positioning design enhanced the acquired images. Hence, less image processing techniques are needed. However, the adaptive noise-removal filter for parallel-beam CCD-based optical CT scanner improves image reconstruction without performing an average technique for each projection. The results indicated that a fast, accurate, and high-resolution dosimeter can be achieved by improving the positioning accuracy, uniform light plan, and image processing technique.

5. Acknowledgements
This work was funded by the National Science Council, Executive Yuan, Taipei, Taiwan under Grants NSC 102–2314–B–166-003, NSC 101–2314–B–166–005, and NSC 99–2632–B–166–001–MY3.

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