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Three-dimensional radiation dosimetry with optical projection tomography

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Abstract. Here we present initial results on the study of the dosimetric properties of a normoxic N-Vinylpyrrolidone based polymer gel dosimeter using a newly developed optical projection tomography (OPT) system. The system employs a sensitive CCD camera, a rotation stage allowing full 360 deg rotation and a wide field homogeneous light source which transilluminates the gel sample. This setup is capable of producing high resolution images of the light attenuation map inside the sample’s volume in three dimensions (3D). The experimental procedure involves the capturing of two-dimensional projection images of the polymer sample in rotation steps of 1 deg. Data analysis is performed by back projecting the photons using an inverse Radon transform resulting in the reconstruction of 3D images of the attenuation coefficient. The resulting 3D attenuation map of the irradiated volume can be directly correlated to the radiation dose imparted. The OPT system may operate in ‘dry’ conditions without the use of any refractive index matching fluids. The sensitivity and dynamic range offered by the methodology covers the range of radiotherapy doses in modern clinical practice.

1. Introduction
Optical projection tomography (OPT) is a new imaging technique, which has been successfully used in genetic research for three-dimensional imaging of small animal models. OPT may be considered the optical equivalent of x-ray CT scanning, provided that the sample under investigation is transparent and the photons are traveling through the sample without any significant absorption or scattering. Three dimensional radiation dosimeters including polymer gels and radiochromic dosimeters fulfill the above requirement. Being originally translucent, their optical properties are appropriately modified in the presence of ionizing radiation. Several optical instrumentations have been developed and evaluated to determine the imparted dose through the quantification of the changes in the optical properties of the irradiated dosimeters. Guo et al. demonstrated accurate 3D dosimetry using the PRESAGETM/optical-CT dosimetry system incorporating a commercial, laser-based optical-CT dose-readout scanner (OCTAPUSTM, MGS Research Inc.). More recently, Sakhalkar et al. in an attempt to reduce scanning time, demonstrated the application of an optical CT scanner, which incorporates a uniform-broad beam
source, customized image forming optics and a charged coupled device (CCD) camera. Despite the advances in the research and development of the 3D radiation dosimetry techniques much effort is still placed towards the development of practical methodologies which could be conveniently applied in the routine radiation therapy practice.

In this study we present initial results on the readout of a normoxic N-Vinylpyrrolidone based polymer gel dosimeter with a newly developed optical projection tomography (OPT) system.

2. Materials and Methods

2.1 Gel Preparation
A new normoxic N-Vinylpyrrolidone based polymer gel dosimeter with tetrakis (hydroxymethyl) phosphonium chloride (VIPET) was employed in this study. The VIPET polymer gels were composed of 4% wt VIPE, 4% wt bis, 7% wt gelatin, and 5mM THPC. The manufacturing procedure was performed in normal atmospheric conditions under a fume hood as follows: the gelatin was added to the double distilled deionized water at room temperature (25 °C) and allowed to dissolve. The solution was then heated to 50 °C and once the temperature was stabilized the bis was added. Heating was achieved through a hot-plate and stirring unit. When the solution became transparent, about 20 min later, the mixture was cooled down to approximately 32 °C and VIPE was added. Once the constituents were completely dissolved after about 5 min, THPC (Sigma-Aldrich) was added in the solution. Three minutes after the addition of THPC the gel was transferred to cylindrical glass vials. The vials were tightly sealed with their caps and parafilm. The gels were allowed to solidify overnight before irradiation at room temperature.

2.2 Irradiation
Five cylindrical glass vials (22 ml) containing the VIPET gel material were irradiated to five radiation doses up to 32 Gy, using a 6 MV LINAC x-ray beam. A parallel opposed dual beam arrangement was applied to produce a uniform dose distribution throughout the entire gel sample. The above samples provided the dose calibration data. Another cylindrical glass tube (150 ml) containing the VIPET gel was irradiated coaxially with the same x-ray radiation beam in a 2 x 2 cm² arrangement. That beam delivered 8 Gy at the depth of the maximum dose.

2.3 Optical projection tomography apparatus
A schematic drawing of the OPT apparatus is shown in figure 1. A broadband light field illumination is provided by a LED array, which is consisted of 30 diodes. The gel sample is positioned on a motorized rotation stage (8MR190-2, Standa, Lithuania) the movement of which is controlled from a personal computer via a microcontroller. The specimen is illuminated through a light diffuser which is placed in between the LED array and the gel sample. The sample is rotated stepwise through a 360° revolution with an image projection captured at each step. The rotational step was 1 deg with a total of 360 images acquired in a complete specimen revolution. Typical exposure times ranged from 200 ms to 1000 ms per projection and the total imaging time ranged from 4 min to 8 min. Capturing of the projection images is performed with a monochrome 12 bit, 640 x 480 pixel, CCD camera (Sony, model: ICX-414AL) through a zoom lens. The camera uses the IEEE-1394 data transferring protocol and it is capable of acquiring images at a rate of up to 86 frames/s.
The iris diaphragm of the zoom lens is set such that the depth of focus spans the full diameter of the gel container. In-focus data are thus recorded from all parts of the gel volume for every image projection. Specially developed software (in-house LabView code) is employed for the control of the camera and the rotation stage as well as the 3D reconstruction of the acquired projection data. Image projections are transformed according to Beer’s law to derive sums of attenuation coefficients. The CCD is oriented such that the rows of CCD pixels are aligned perpendicular to the rotational axis. The temporal sequence from a row of pixels forms a sinogram that reconstructs the corresponding slice using standard convolution filtered back-projection with the Hamming filter. Prior to the 3D reconstruction the software determined automatically the position of the specimen’s rotational axis. This was done by reconstructing a series of images with differently assumed positions of the rotational axis, and calculating the variance of each reconstruction. The reconstructed image with the maximum variance corresponds to the least offset between the true and the assumed position of the rotational axis and is thus the least blurred.\textsuperscript{[13],[14]}

The reconstruction uniformity and spatial resolution of the OPT system were evaluated. In particular, an unirradiated gel sample was scanned to evaluate the imaging reconstruction uniformity and a thin optical fiber 360 μm in diameter was scanned to evaluate the imaging resolution.

3. Results and Discussion
Figure 2 illustrates the OD-dose response curve obtained at 24 h post-irradiation using the OD data obtained from the gel vials irradiated to doses between 0 and 32 Gy. The linear regression analysis showed that OD and dose are linearly related in the range from 0 to ~ 20 Gy (OD = 0.017 x D – 0.0023, \( r^2 = 0.999 \)).
Figure 2. Optical density (OD) vs. dose calibration data. A linear response is preserved for doses up to approximately 20 Gy.

Figure 3(a) shows a projection image of the unirradiated gel sample. The dark regions along the boundaries between the gel and the cylindrical glass wall are attributed to the differences in the refractive index among the gel material, glass and air. Figure 3(b) shows a reconstructed axial slice along the red dashed line of (a), and Figure 3(c) illustrates a thick line profile curve along the area enclosed within the white frame of (b). The profile curve shows that the unirradiated gel material is reconstructed in ‘bowl’ shaped image slices. The difference in the reconstructed values between the center and the periphery regions of the homogenous gel is up to 40%. This difference was attributed to the fact that the gel vial is surrounded by air without being immersed to refractive index matching fluid.

Figure 4(a) shows a projection image of the irradiated gel sample and figure 4(b) shows a reconstructed axial slice along the red dashed line of (a). Figure 4(c) illustrates a thick line profile curve along the area enclosed within the white frame of (b). The reconstructed profile values of figure 4(c) were normalized against the corresponding values of the unirradiated gel (figure 3c) to compensate for the ‘bowl’ effect. The derived values may be converted to optical density and subsequently to dose values based on the OD-dose calibration equation given in Figure 2.
Figure 3. (a) A projection image of the unirradiated gel, (b) reconstructed axial slice at the level of the red dashed line, and (c) thick-line profile curve of the reconstructed values along the area within the white frame in (b).

Figure 4. (a) A projection image of the 2 x 2 cm² 6 MV beam irradiated gel, (b) a reconstructed axial slice at the level of the red dashed line, (c) a thick-line profile curve of the reconstructed values along the area within the white frame in (b).

At the zoom level setting used in this experiment the reconstructed image slices are approximately 1 mm thick. The full width at half maximum of the reconstructed fiber was 860 μm. The calculated MTF is greater than 10 % down to approximately 1.1 mm⁻¹, which is better than the 2 mm⁻¹ limit prescribed by the ICRU for radiation therapy dosimetry. Better z-axis and x-y spatial resolution is anticipated at a higher zoom level.
4. Conclusion
The OPT apparatus presented in this study may operate without the need of cumbersome refractive index matching liquid baths. This allows the readout process to be performed in ‘dry’ conditions with the gel container surrounded only by air. Further studies are needed to evaluate the performance of the OPT system presented in this study. These studies need to evaluate various parameters such as the geometric accuracy and distortion, linearity, signal to noise and contrast to noise ratios, and the presence of image artifacts. The initial findings presented in this study indicate that 3D dosimeters might be potentially scanned without being immersed in a refractive index matching fluid facilitating their convenient use for the verification of routine radiation treatment plans.

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