Verification of micro-beam irradiation

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Abstract. Micro-beam Radiation Therapy (MRT) is an experimental radiation therapy with provocative experimental data indicating potential for improved efficacy in some diseases. Here we demonstrated a comprehensive micro-beam verification method utilizing high resolution (50µm) PRESAGE/Micro-Optical-CT 3D Dosimetry. A small PRESAGE cylindrical dosimeter was irradiated by a novel compact Carbon-Nano-Tube (CNT) field emission based MRT system. The Percentage Depth Dose (PDD), Peak-to-Valley Dose Ratio (PVDR) and beam width (FWHM) data were obtained and analyzed from a three strips radiation experiment. A fast dose drop-off with depth, a preserved beam width with depth (an averaged FWHM across three beams remains constant (405.3µm, sigma=13.2µm) between depth of 3.0~14.0mm), and a high PVDR value (increases with depth from 6.3 at 3.0mm depth to 8.6 at 14.0mm depth) were discovered during this verification process. Some operating procedures such as precise dosimeter mounting, robust mechanical motions (especially rotation) and stray-light artifact management were optimized and developed to achieve a more accurate and dosimetric verification method.

1. Introduction
Conventional Radiation Therapy (such as Intensity Modulated RT (IMRT) and 3D Conformal RT) can achieve excellent target conformity (with uniform dose) and normal tissue sparing in many sites. However, some diseases such as gliosarcoma require better performance in control rates. Conclusions drawn from previous small animal irradiation experiments confirm the clinical potential and rationale for MRT treatment of deep-seated aggressive brain tumors in developing neurological tissue [3]. A compact MRT system for small animal irradiation has been developed at University of North Carolina (UNC, USA), based on carbon nanotubes (CNT) field emission technology. The CNT MRT system employs linear segmented cathode array and collimating alignment system. Although some preliminary 2D dosimetry measurements have been performed [3, 4], 3D dosimetry characterization has yet to be characterized.

2. Method and Materials
In order to characterize the micro-beam radiation delivered by the CNT MRT system, an ultra-high-resolution prototype 3D dosimetry system was constructed and optimized. This dosimetry system includes two parts: radiochromic dosimetry material (PRESAGE®) and an Optical-CT imaging...
system (Duke Micro Optical-CT Scanner (DMicrOS)) (shown in figure 1(a) and (b)) for readout purpose. The system can achieve 50 μm isotropic high-resolution 3D reconstructed dosimetry data.

Figure 1. (a): Schematic of the prototype DMicrOS optical-CT scanning system (a scaled down version of the system introduced in [1]) (b): Photograph of the DMicrOS system in the lab – max field-of-view is ~3cm.

PRESAGE® was first introduced in 2006 as a material compatible with 3D dosimetry by optical-CT [2]. It consists of a polyurethane matrix, doped with a halogenated hydrocarbon free radical initiator and the leucodye leucomalachite green (LMG). Free radicals generated from the radiolysis of the halogenated hydrocarbon bond upon irradiation oxidize the LMG dye leading to a change in absorbance. The change in absorbance is linear with respect to the absorbed radiation dose [5].

A small PRESAGE® cylindrical dosimeter was irradiated by CNT MRT with nominal dimension (at the isocenter) of 65mm long x 300μm wide each beam at an energy of 160 kVp (nominal entrance dose was 32 Gy). The count image and OD image of post irradiated dosimeter are shown in figure 2 (a) and (b).

Figure 2. Three micro-planar beam irradiation pattern in the irradiated dosimeter (2.5cm diameter, 2.2 cm height). Top row shows a single projection image as counts (a) and ODs (b). Bottom row shows slices through the reconstructed 3D dose distribution sagittal view (c) and a mid-plane axial view (d).

The dosimeter was affixed and spatially registered to the rotating stage by two holes drilled into the dosimeter bottom that corresponded with metal registration keys on the stage. A weight was placed on top of the dosimeter to prevent dosimeter drift. The optical system was carefully aligned, and the fluid
in the tank was matched to the refractive index of the dosimeter. 720 projections were acquired during a 360° rotation as required for a 50μm resolution 3D reconstructed image. A custom, in-house MATLAB-based GUI was employed for 3D reconstruction.

In order to reduce intensity variation brought by the edge of the dosimeter as well as to reduce the noise, a 200 pixel (10 mm) central section of the reconstructed data was averaged and saved as a 2D matrix, which can be used to analyze the data. 50μm (isotropic) 3D dosimetry was performed on all dosimeters using the DMicrOS. The Percentage Depth Dose (PDD), Peak-to-Valley Dose Ratio (PVDR) (taken from averaging three peaks’ dose values divided by two valleys’ dose values), and beam width (FWHM) were obtained as functions of depth.

3. Results and Discussion

3.1. DMicrOS basic testing

Basic testing results of the DMicrOS system are shown in figure 3, indicating Modulated-Transfer-Function (MTF), dynamic range, spatial resolution limit in object space, and Signal-to-Noise-Ratio (SNR).

| Dynamic range (counts) | Pixel size (μm) | Dark noise level (μm) | Signal to Noise Ratio | Largest Field-Of-View (FOV) |
|------------------------|----------------|-----------------------|-----------------------|-----------------------------|
| 100~3900               | 29.6           | Mean: 3.8 count: σ=0.04μm: | 46.6 | 47.6 mm (HFOV) x 35.8 mm (VFOV) |

Figure 3. DMicrOS basic specifications

3.2. 3D dosimetric measurements

3.2.1. PDDs. The PDD measurements were normalized to values at 3mm depth. PDDs of the three beams were plotted as a function of depth (shown in figure 4(a)). Depth was measured along the beam path. A sharp dose drop-off (86.5% at a depth of 14 mm) can be seen in table 2.

Figure 4. PDDs (a) and FWHMs (b) of three beams.
3.2.2. FWHMs. The FWHMs of the three beams were plotted as a function of depth (shown in figure 4(b)). Depth was measured along the beam path. The variance with different depths is very small ($\sigma \sim 13.2 \mu m$). (shown in table 1)

| Entrance dose | Average FWHM (between depth of 3mm-14mm) across three beams |
|---------------|---------------------------------------------------------------|
|               | mean | Std ($\sigma$) |
| 32 Gy         | 405.3$\mu$m | 13.2$\mu$m |

3.2.3. PVDRs. The PVDR was calculated from averaging of maximum values of each peak divided by average of minimum values of each valley. PVDR was plotted as a function of depth (shown in figure 5). Depth was measured along the beam path. As depth increases, PVDRs also gradually increases from 6.3 (at depth of 3mm) to 8.6 (at depth of 14mm) shown in table 2.

| Entrance dose | Average PVDR at depth 3mm | Average PVDR at depth 14mm |
|---------------|---------------------------|---------------------------|
| 32 Gy         | 6.3                       | 8.6                       |

3.3. Comparison with 2D verification
Comparing our results with the independent measurements from UNC’s [3,4] the beam width measurements are very consistent (within 0.04% - table 3). However, a large difference can be seen in PVDR measurements (15.6%-34.0% - table 3). The difference may arise in part from the fact that the 3D measurements were made at depth, while the 2D film measurements were made at the surface. Another potential source of uncertainty is the influence of stray light in this extreme irradiation geometry. According to the report by UNC research group, the PVDR values are consistent between their 1D (with their Nano-crystal dosimeter) and 2D (with EBT2 film) measurements (within ~1% difference). Further work is required to investigate the cause of the differences.

Table 3. Comparison 3D verification with 2D verification.

| Beam width | PVDR     |
|------------|----------|
| UNC--2D    | 350      | 11.5     |
| Duke--3D   | 350.5    | 21.9-60.4|
| %Difference| 0.04%    | 15.6%-34.0%|

4. Conclusion
MRT dosimetry is extremely challenging due to the utilization of ultra-small field sizes and lower energy beams. The prototype ultra-high resolution optical-CT 3D dosimetry system introduced here showed some characteristics of micro-beams: A fast dose drop off, stabilized beam width and gradually increased PVDRs with the depth. These results are promising but suggest achieving high-resolution 3D dosimetry requires exceptionally careful procedures. Previous efforts to optimize fluid
matching, standardize the operating procedures, improving the precision of dosimeter mounting and motion have shown promise. Next step involves developing methods for scanning/artifact correction.

5. References
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