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Dosimetric assessment of the PRESAGE dosimeter for a proton pencil beam

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Abstract. The objective of this study is to assess the feasibility of using PRESAGE dosimeters for proton pencil beam dosimetry. Two different formulations of phantom materials were tested for their suitability in characterizing a single proton pencil beam. The dosimetric response of PRESAGE was found to be linear up to 4Gy. First-generation optical CT scanner, OCTOPUS™ was used to implement dose distributions for proton pencil beams since it provides most accurate readout. Percentage depth dose curves and beam profiles for two proton energy, 110 MeV, and 93 MeV, were used to evaluate the dosimetric performance of two PRESAGE phantom formulas. The findings from this study show that the dosimetric properties of the phantom materials match with basic physics of proton beams.

1. Introduction
A proton beam has the advantage in its characteristic distribution of dose with depth. The depth dose peaks to highest value near the end of its range followed by a rapid falloff to zero. These physical characteristics of proton beams offer higher dose conformity to the tumor and lower dose to the surrounding normal tissues than a photon beam can achieve. There are two beam delivery systems in terms of beam spreading to its desired field cross section: 1) passive beam spreading by thin sheets of high-atomic materials; or 2) pencil beam scanning by magnets. Proton pencil beam scanning can provide precise and efficient treatment delivery for both conventional and intensity modulated proton therapy (IMPT) techniques. Detailed three-dimensional dosimetric information for a proton beam is crucial for accurate treatment planning design and treatment delivery due to the sharp dose falloff at the end of the beam range and laterally at the field edges [1-3]. It is more challenging to measure the 3-D dose distribution of a pencil beam (1 - 1.5 cm diameter) because of its small field size as well as the complexity of dose changes in various directions.

Both polymer gels [4] and PRESAGE [5, 6] radiochromic plastic dosimeter, in conjunction with optical CT scanner [7, 8], have been employed to verify 3-D dose distribution for complex treatments with photon beams, such as IMRT and stereotactic radiosurgery [9, 10]. These studies have shown promising results in providing a 3-D dosimetry tools for photon external beam treatments. There are some recent studies on proton dosimetry using polymer gels [11] and PRESAGE dosimeters [12], with optical CT scanners as readout systems. However, there has not been any report on dosimetry of a
single proton pencil beam. This study is the first investigation in characterizing the dosimetry of a single proton pencil beam using PRESAGE radiochromic dosimeters and an optical CT scanner.

2. Materials and Methods

In this study, cylindrical PRESAG® dosimeters and an optical CT scanner, OCTOPUS™ (MGS Research Inc., Madison, CT) were used to implement dose distribution measurements for proton pencil beams at the Northeast Proton Therapy Center (NPTC), Massachusetts General Hospital (MGH). Each cylindrical PRESAGE phantom of 11.4 cm diameter and 10 cm height, modified to optimal dose-response characteristics, was used for proton pencil beam measurements. Two different dosimeter formulas were used for measurements. One formula has a physical density of 1.09 gm/cm³ and an average atomic number of 8.9, and the other formula has a physical density of 1.06 gm/cm³ and an average atomic number of 7.5. One objective of this study is to assess which PRESAGE formulation can be clinically used as a proton phantom. Two single proton pencil beams, with energies of 110 MeV and 93 MeV, were used for studies. These two proton energies were chosen because their ranges, 9.5 cm and 6.5 cm, respectively, are within the dosimeter length dimension. The dosimeters were maintained at a temperature of 7°C before and after irradiation. The dosimeters were set to reacclimatize to room temperature of about 22°C before irradiation and optical-CT readout.

In order to examine the optical density response of PRESAGE dosimeter versus proton dose, the optical density dose response was studied by irradiating the dosimeters with a 4 x 4 cm square field, uniform scattered clinical beam, to various known doses (up to 400 cGy). Four cylindrical phantoms were used for proton pencil beam dosimetry study. Each phantom was irradiated with three horizontal proton pencil beams (FWHM 1.1-1.4 cm) from one end, since the size of the phantom can easily accommodate three pencil beams. For each energy, a wide range of doses from 50 cGy up to 150 cGy at the entrance were delivered among 6 beams. This arrangement allows us to find the optimal dose range for best dose image reconstruction. The dosimeter sample was scanned with 1mm pixel resolution using the optical CT scanner, OCTOPUS™. Details of the operating principles, 3-D dose reconstruction, and instrument architecture of the optical scanner were described previously [13, 14]. For comparative dosimetry, Gafchromic films, placed at various depths in a solid water phantom, were irradiated with a proton pencil beam using the same beam parameters.

2. Results and Discussion

As shown in figure 1, the optical density of the irradiated PRESAGE versus dose was found to be linear from 0 to 2 Gy. Therefore, the optical density distribution in the irradiated phantoms represents the dose distribution.

Figure 1: Dose response curve for PRESAGE, calibrated with 4x4 cm uniform scattered beams at various doses.

Figure 2: PRESAGE phantom irradiated with proton pencil beams. The Bragg peak with a sharp dose falloff can be observed.
Figure 2 shows a clear image of Bragg peak for a 93 MeV proton pencil beam. The phantom formula used in this irradiation has a physical density of 1.06 gm/cm³, and an average atomic number of 7.5. Note that there is a beam spread near the end of the proton range.

In figure 3, the integral dose at each depth was obtained over the beam cross section. The phantom depth was scaled by its physical density relative to water (1.09), and yields an equivalent depth in water. The integral doses for PRESAGE, at the Bragg peak and its upstream region, are 10-25% lower compared to the results obtained from film measurements in solid water. The differences can be largely attributed to the mass stopping power ratios between PRESAGE material and water. Mass stopping power for protons is greater in low Z materials than in high Z materials. The phantom material used for the study in figure 3 has an average atomic number of 8.9, and a physical density of 1.09 gm/cm³.

Figure 4 presents the integral percentage depth dose measured from PRESAGE for a 93 MeV proton pencil beam. The 93 MeV proton pencil beam was achieved by passage of 110MeV proton pencil beam through Lucite slabs with density thickness of 2.125 gm/cm². As expected, the distal dose falloff for 93 MeV is much less sharper than that for 110 MeV. The phantom material used for the study in figure 4 has an average atomic number of 7.5, and a physical density of 1.06 gm/cm³. Future study will be focused on the development of a new formulation that is optimal for proton pencil beam dosimetry.

The relative dose profiles at different depths for a 110 MeV pencil beam was plotted in figure 5. The lateral spread increases with the depth since scattering in a given material increases as the proton slows down. The angular spread is approximately a Gaussian distribution. Figure 6 shows 2-D dose distribution in coronal direction. The FWHM is between 1.3-1.4 mm. The lateral dose falloff compared to the results from film measurement is under investigation.

3. Conclusion
We have evaluated the dosimetric performance of PRESAGE dosimeters for proton pencil beam dosimetry, at 110 MeV and 93 MeV. The findings from this study suggest that it is feasible to use PRESAGE dosimeter for proton pencil beam study. Future study will be focused on comparison with proton pencil beam data, as well as evaluation of dosimeter formulation.
Figure 5: Dose profiles at different depths for a 110 MeV proton pencil beam, obtained from PRESAGE measurements.

Figure 6: Coronal isodose lines for a 110 MeV proton pencil beam at 7.5 cm depth, from PRESAGE measurements (99%, 90%, 80%, 70%, 60%, 50%, 30%, 10%)

4. References