Feasibility of PET/CT 3-D dosimetry for proton-activated PRESAGE® dosimeters

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Abstract: A feasibility study is considered using PRESAGE® dosimeters as a direct dosimetry comparison tool to correlate proton activation to dose in a clinical beam. Proton activation measured by PET/CT has been studied as a future tool method for in vivo dosimetry. PRESAGE® is a 3D offline dosimeter that has a material composition giving it a longer activation decay time than similar dosimeters allowing easier measurements. In this study, the PRESAGE® positron emissions were measured by PET and directly compared to dose measurements made by optical-CT to make spatial comparisons of dose and proton activation. Profiles along the central axis of the beam found a shift in the distal-80% resulting in the proton activation profile being 1 cm shallower than the dose profile. Cross beam profiles demonstrated little discrepancy between long (3 hour) and short (30 minute) PET scan times.

1. Background

Previous studies have investigated the potential of proton positron activation as a method of noninvasive in vivo dosimetry using positron emission tomography (PET) [1]. Early work has theorized that positron activity distributions could be used to reconstruct dose distributions [2], but prior to clinical use, a better correlation must be developed between these two distributions. The cross-section for activation of positron emitters is dependent on the energy of the proton beam that changes with depth in tissue, leading to a shift in areas of maximum positron activity away from the Bragg Peak. Using a separate device for relative dosimetry can lead to dose mapping uncertainties [3]. A 3D dosimeter [4] can allow mapping of proton dose distribution to the PET activity measurement within a single detector and reduce these uncertainties.

Previous studies have tested polymer gels to map positron-emitter activation. Gels rely primarily on 15O emitters which have half-lives of ~2 minutes making rapid readout essential [5]. We have investigated use of the radiochromic polyurethane dosimeter PRESAGE® [6] to correlate the proton dose distribution to the PET activity measurement within a single detector. The polyurethane in PRESAGE® is primarily composed of carbon (approx. 62% w/o) which has a more manageable half-life of 20 minutes. The PRESAGE® formulation used was developed to minimize the sensitivity to proton LET and has similar density and RLSP to tissue [7].
2. Methods
Cylindrical PRESAGE® dosimeters approximately 6 cm in height and 6 cm in diameter were used in this study. PRESAGE® is homogeneously radiation sensitive without the necessity of a container which allows dosimetric measurements through its volume. The dosimeters used in this study were manufactured by Heuris Pharma, LLC. Irradiations were performed at the M. D. Anderson Proton Therapy Center (PTC).

![Figure 1. PRESAGE® dosimeters in the water phantom prior to proton irradiation.](image)

Three cylindrical dosimeters were irradiated to 500 cGy with 180-MeV energies in a single, wide-beam shot with passive double scattered protons. Irradiations were done in a water phantom, shown in figure 1, with the dosimeters placed approximately 13.8 cm deep. An 18x18 cm$^2$ field size was used to irradiate all three dosimeters at once with the beam directed along the dosimeter’s central axis to deliver a 2 cm spread-out Bragg peak (SOBP) 2 cm deep in the dosimeter. The lower halves of the dosimeters were left unirradiated to measure PET activity in steep dose gradients across the full dose profile.

After irradiation, the dosimeters were rushed to a nearby PET/CT for the first stage of imaging on a GE Discovery 690 FX. Between irradiation end and scan beginning was just under 15 minutes which is less than one half-life of the activated $^{11}$C. Pixel spacing of 1.0x1.0x1.0 mm$^3$ was used for the CT. The PET scan was then run for 3 hours allowing acquisition of the full decay of the activated isotopes. The CT was used for attenuation correction of the PRESAGE®. Immediately after, the dosimeters were analyzed using the Duke Mid field-of-view Optical CT Scanner (DMOS) at a nearby facility to matching pixel sizes. The PET image was compared with the calculated dose distribution using the Computational Environment for Radiotherapy Research (CERR) software platform.

3. Results
PET reconstructions of the first 30 minutes, 1 hour, 2 hours and 3 hours were correlated to the dose measurement of the optical-CT to determine time sensitivity of the activation decay. Measurements of the PRESAGE® dosimeter taken with PET/CT and optical-CT are shown in figure 2 and figure respectively. The PET/CT shows the effect of dose as positron emission while the optical-CT measures dose by a change in the optical density in the dosimeter.

A comparison of the two imaging modalities demonstrates the proton activation geometrically with respect to the beam profile. A visual comparison shows that the proximal region of the SOBP displayed the highest PET activity, meaning the positron hotspots shifted towards the beam entrance compared to the measured dose. This correlation was consistent with previous proton activation studies [5]. A profile along one irradiated PRESAGE® central axis, along with ion chamber data of the beam in a water phantom and corrected for RLSP, reflects this shift in the activity peak and is shown in figure 4. At the distal 80%, an approximately 1 cm discrepancy between normalized dose and PET activity was found.
Spatial distributions between the measured dose and PET signal are perhaps the most relevant for in vivo verification. The proximal region of the dose is the region with the highest activity while less signal is detected in the distal side of the SOBP. The falloff region following the SOBP in which the beam energy has significantly decreased shows no signal as protons energies have fallen below the activation thresholds. A lateral axis profile comparison shows another cross-section of relatively uniform dose that demonstrates the positron activity across a monoenergetic profile and is shown in figure 5. PET measurements showed minor improvements in stability for scans beyond 30 minutes. Profile discrepancy in the central axis data showed up to a 5% discrepancy comparing scans of 30 minutes and 3 hours which fell to less than 2% comparing scans of 1 hour and 3 hours. Similar trends were observed in the lateral profiles.
4. Discussion and Conclusions
PRESAGE® dosimeters offer a unique potential to accurately correlate dosimetric and PET activation information. Implementation in an anthropomorphic phantom could be used to study representative treatment plans.

5. References
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