The Bragg peak may undermine the FLASH effect: Results from a novel plastic scintillator

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Purpose: While biological studies of the FLASH effect in proton beams have mainly been performed in the plateau region of at maximum beam energy and current, this type of delivery has limited clinical applications and plans to treat patients clinically with FLASH-RT naturally expect to capitalize on the Bragg peak. However, as the proton spot widens with depth, the time required to deliver the entire dose to any single point increases. The dose rate decreases, making ultra-high dose rate (UHDR) harder to achieve over large areas. Importantly, however, the dose rate is difficult to measure directly.

Methods: Time, dose, and energy linearity of a novel fast-resolving (2.5 ms) novel plastic scintillation detector (PSD) were characterized against an ionization chamber. The percent depth-dose of a Varian ProBeam 250 MeV proton beam scanned across a small area (3.5×3.5 cm^2) was measured at depths of 3–40 cm in solid water. The PSD was used to evaluate the instantaneous and voxel-averaged dose rate (VADR) as a function of depth for conventional (2 nA nozzle current) and UHDR (100 nA) beams.

Results: The PSD is shown to be linear with time (±2.5 ms) and radiation dose (±2%). The PSD and IC measurements agree well as a function of depth (and therefore energy) within ±2% for depths <34 cm, after which expected quenching effects are observed in the PSD. The VADR was measured at different depths and for different spot spacing. While the VADR was shown to be relatively independent of spot spacing, particularly near the Bragg peak, the dose rate does vary significantly with depth. As the proton beam penetrates deeper in solid water, the spot size increases due to scattering and divergence. As a result, fewer spots contributed dose to the scintillator signal when it was positioned in the entrance region as compared to the Bragg peak region, where spot size is maximal. Consequently, the dose delivery time at the central axis increased by a factor of ~1.7 between the entrance and the Bragg peak regions. The average dose rate consequently varies from 52.7 Gy/s at the entrance to 29.3 Gy/s at mid-depth, to 70.4 Gy/s at the Bragg peak. While the decrease in average dose rate is mitigated by dose escalation at the Bragg peak, the maximum instantaneous dose rate decreases from 472 Gy/s near the entrance to 236 Gy/s at the Bragg peak.

Conclusions: The PSD has proven useful for investigators to evaluate the complex relationship between dose rate and PBS UHDR beam characteristics. There is a loss of dose rate near the Bragg peak due to spot widening which may acutely impact our ability to exploit the FLASH effect for sparing normal tissues upstream of the intended treatment area. Further preclinical and clinical investigations on whether the FLASH effect is maintained near the Bragg peak are necessary before this technique can be widely translated to the clinic.