A GEANT4 SIMULATION STUDY FOR IN-VIVO RANGE VERIFICATION IN PROTON THERAPY

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Introduction: Prompt gamma (PG) rays, a secondary by-product emitted from particle therapy, have been proposed for *in-vivo* beam range verification during treatment delivery. PG rays offer real-time tracking of the Bragg peak (BP), however their detection is challenging since they are generated from different nuclear reactions and have a broad energy spectrum with intereference from neutrons and stray gamma rays. There have been a variety of approaches proposed to utilise the PG information for *in-vivo* beam range verification [1-3]. In this work, Geant4 Monte Carlo [4] (MC) simulations have been used to study the energy spectral, spatial and time-of-flight (TOF) characteristics of the PG emission signal from a proton radiation field of varying energy. These studies would provide valuable information for the development of clinically suitable and reliable PG-based beam range systems.

Materials and Methods: The Geant4 MC toolkit has been adopted to characterise PG emission during proton irradiation of a homogeneous water (H_2O, density of 1.0 g/cm^3) phantom. Proton pencil beams of 62, 150, 200 and 250 MeV were simulated. The phantom was sphere of size ϕ40 cm. An ideal detecting sphere (ϕ100 cm) surrounding the phantom registers PG rays and neutrons that reach its surface once emitted from the phantom. The TOF was taken as the time from proton incidence on the phantom to detection of the secondary particle at the detecting sphere. The Geant4 physics included electromagnetic (Livermore Low Energy Package) and hadronic physics (QGSP_BIC_HP for protons, neutrons and pions, Binary Ion Cascade models for ions). The production threshold of secondary particles was fixed to 1 mm.

Results: The gamma energy spectra generated in the water phantom show characteristic PG peaks at 4.44 MeV (^{12}C*), 5.21 MeV (^{15}O*) and 6.13 MeV (^{16}O*). A strong longitudinal distribution correlation between PG and BP position was seen. The range and corresponding PG emission distal fall-off for each beam energy considered are given in Table 1. An energy window selecting the PG peaks, 3-7 MeV, show a closer correlation to the proton beam range.

The PG spatial distribution in the ideal detecting sphere showed isotropically azimuthal emission but non-isotropically axial emission. PG emission is slightly backward peaked relative to the BP position, while neutrons are mainly emitted forward. As the beam energy increases, the PG TOF peak mean shifts to longer TOF values while the peak width/integral increases; this can be attributed to the greater distance of travel by the protons. Neutrons are not predominantly emitted until ~4 ns, which could suggest a means of discriminating PG rays from the background and hence improve the signal-to-noise ratio of PG detection.

Table 1. Proton beam range and the corresponding PG longitudinal distal fall-off, as well as TOF mean and integral values.

Beam energy (MeV)		62	150	200	250
Range (mm)	Proton	32	155	256	375
	Total gamma	27	150	250	368
	PG	28	151	252	370
PG TOF	Mean (ns)	1.8	2.6	2.9	2.9
	Integral	0.14	0.46	0.66	0.88

10^7 incident protons. Range values (±1 mm) are taken at 80% fall-off. PG, 3-7 MeV. TOF integral is yield per incident proton. The statistical uncertainty affecting the results is within 1%.

Conclusion: The emission and detection characteristics of PG rays and neutrons were studied with a water phantom and varying proton beam energy. Our results show that an energy window selecting only the PG peaks could offer improved information for beam range verification. There is a preferential axial angular position for PG detection at a slight backward direction relative to the BP position. The PG TOF spectra was seen to change with varying beam energy, and hence beam range, suggesting a potentially better way of using PG for beam range verification. A recent paper from Krimmer et al. [3] showed that the count variations of the PG TOF peak integral have a strong correlation with the beam range deviation. Further investigations into this technique for range verification during proton therapy (and other particles such as ^{12}C and ^{4}He) are underway.

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