Yields of positron-emitting nuclei (^{10}C, ^{11}C, and ^{15}O) induced by protons and carbon ions: a simulation study with Geant4

Introduction: Beams of protons and carbon ions are used in particle therapy for conformal irradiation of a tumor while sparing surrounding healthy tissues and organs at risk. Positron emission tomography (PET) is potentially a powerful tool for monitoring the precision of dose application in charged hadron therapy. It is based on the detection of the annihilation γ-rays following the decay of β+ emitters (typically ^{10}C, ^{11}C, and ^{15}O) produced via nuclear fragmentation reactions between the incident particle and the target nuclei of the irradiated tissue. The monitoring is achieved by comparing the measured β+ activity distribution with an expected distribution calculated on the basis of the treatment plan, patient's anatomical information and the time course of the irradiation. The primary purpose of this investigation is to quantify the yields of positron-emitting nuclei and their yield-depth distribution by utilizing the Geant4 Monte Carlo Toolkit.

Materials and Methods: An application was constructed with the Geant4 Monte Carlo Toolkit utilizing various physics packages (both low and standard electromagnetic packages, parameterized and Binary Cascade inelastic packages, and parameterized elastic packages). A phantom with dimensions of 9 cm x 9 cm x 30 cm consisting of PMMA ($C_5H_8O_2$, density of 1.18 g/cm^3) was irradiated with 70 MeV and 110 MeV protons as well as 204 A MeV and 212.12 A MeV carbon-ions. The beam parameters mimic a pencil-like beam with a position resolution of 10 mm FWHM and a Gaussian energy spread of 0.2% FWHM. In each simulation the energy deposited from the incident primary particles was recorded for every 0.1 mm increment of depth in the phantom. The resulting positron-emitting nuclei (^{10}C, ^{11}C, and ^{15}O) and their total yield of positrons were recorded at both the production point as well as the point of decay in increments of 1 mm.

Results: The overall percentage yields of positron-emitting nuclei per incident particle for both protons and carbon ions are shown in Table 1. The depth-dose curve normalized to Bragg peak as well as the yield of positron-emitting nuclei and their total per incident particle of protons and carbon ions as a function of depth are shown in Figure 1.

Conclusions:

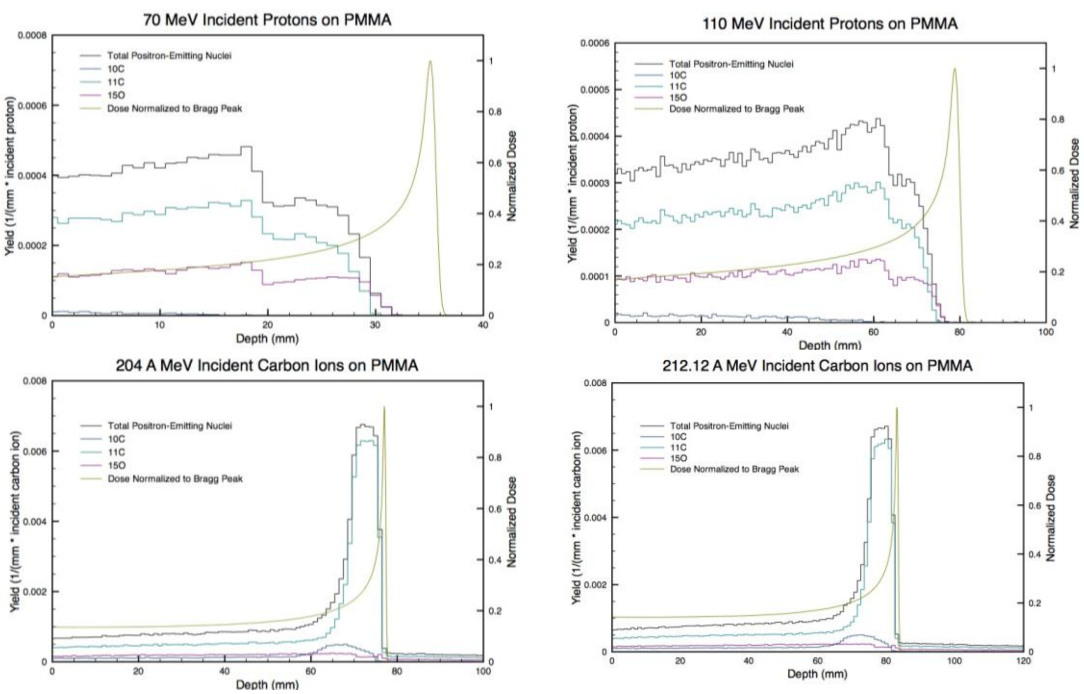
Our yields of positron-emitting nuclei are in excellent agreement with other simulations (for example: FLUKA and MCHIT)[1,2] and experimental data[1,3]. The present work however overestimates the percentage of ^{10}C in the simulations of incident carbon ions compared to the experimental data, and underestimates the percentage of ^{11}C for the simulation of 110 MeV incident protons compared to the experimental data**.** This particular application built within the Geant4 Monte Carlo Toolkit thus predict the amount of positron-emitting nuclei as well as the yield-depth distributions of these nuclei in hadron induced radiation therapy.

Table 1: Percentage yields of positron-emitting nuclei (^{10}C, ^{11}C, and ^{15}O) per incident particle for 70 MeV and 110 MeV protons as well as 204 A MeV and 212.12

A MeV carbon ions.

	70 MeV Incident Protons		110 MeV Incident Protons			204 A MeV Incident Carbon Ion		212.12 A MeV Incident Carbon Ions		
Nuclei	This Work	FLUKA	This Work	MCHIT	Experiment	This Work	Experiment	This Work	MCHIT	Experiment
^{11}C	0.779	0.76	1.75	1.83	2.2 ± 0.3	10.6	9.98 ± 1.26	11.4	11.9	10.5 ± 1.3
^{10}C	0.011	0.007	0.07	0.11	0.09 ± 0.03	1.51	0.75 ± 0.17	1.64	1.97	0.8 ± 0.3
^{15}O	0.366	0.392	0.78	0.8	0.8 ± 0.15	2.04	1.91 ± 0.34	2.19	2.38	2.1 ± 0.3

Figure 1: Depth-dose curve normalized to Bragg peak; yield of positron-emitting nuclei (^{10}C, ^{11}C, ^{15}O, and their total) as a function of depth for a). 70 MeV incident protons (Top-Left), b). 110 MeV incident protons (Top-Right), c). 204 A MeV incident carbon ions (Bottom-Left), and d). 212.12 A MeV incident carbon ions (Bottom-Right).



References:

1. Pshenichnov et al., *Distributions of positron-emitting nuclei in proton and carbon-ion therapy studied with GEANT4*, Physics in Medicine and Biology, 2006. **51**(23): p. 6099-6112

2. Parodi and Enghard, *Potential application of PET in quality assurance of proton therapy*, Physics in Medicine and Biology, 2000. **45:** N151-156

3. Parodi et al., *In-beam PET measurements of β+ radioactivity induced by proton beams.* Physics in Medicine and Biology, 2002. **47**(1): p. 21-36