Physical and Biological Modelling of Proton and Heavy Ion Radiation using Geant4

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Introduction

Radiation dose deposited by protons and heavy ions (HI) increases with depth in tissue, reaching the maximum in the Bragg peak beyond which the delivered dose is approximately zero. These properties result in a superior geometrical dose distribution compared with conventional X-ray treatments. Although nuclear stopping effects are smaller than electronic effects in the energy range used in HI therapy, they are not negligible. Nuclear fragments generated in nuclear break-up reactions can have considerable energy, mass and charge and can cause significant damage in the tumour and in surrounding tissues.

In the current work the Monte Carlo code Geant4 was used to determine the effect of nuclear fragmentation processes on heavy ion dose distributions and their dependence on initial particle energy and the absorber.

Methods and Materials

Using the Geant4 toolkit, a physics list was developed to simulate the transport of protons and heavy ions in water and dense bone. Using a water phantom, the dose distribution for protons, alpha particles, carbon and neon ions of energy 150, 600, 3500 and 7850 MeV respectively in water were calculated. These energies resulted in coincident Bragg peak positions for each ion in water. The dose contributions from individual fragments from the nuclear fragmentation reactions were investigated. The fragments beyond the Bragg peak were analysed for their contributions to the dose "tail". The energy spectra of the secondary neutrons were calculated using 2000 bins of width 0.5 MeV to predict the potential risk to patients.

Results

It was determined that the contributions from fragments, both for water and bone, increased with increasing particle mass, energy and density of medium. Fragments contributed: <1 %, 2.5%, 10% and 17% for protons, alpha, carbon and neon to the total dose in water respectively. Secondary neutron radiation intensity was shown to peak at energies of above 100 MeV when primary ions of clinical energies are used.

Conclusion and Future Work

Geant4 has proven to be a customisable, adaptable and accurate tool for the investigation of protons and heavy ions in medical applications. With the use of Geant4, carbon ions are the optimal heavy ion particle for use in external beam radiotherapy based on dose distribution, RBE at the Bragg peak and nuclear fragmentation. Using the recently developed Geant4-DNA physics list, the track structure of protons and heavy ions is currently being investigated. The addition of new cross sectional data for materials other than water will enable damage to cell structure to be accurately simulated. With accurate track structure data for heavy ions, simulations of cell necrosis and apoptosis due to individual ionisation events can be performed.