Improving Computational Efficiency in Monte Carlo Simulations of a Passive Scattering Proton Therapy Treatment Head

Innovation/Impact

We consider this work to be innovative because it shows techniques which allow to increase the computational efficiency in Monte Carlo simulations of a passive scattering proton therapy nozzle, when the aim is generating a phase-space file of protons. These techniques were applied in a simulation of a real nozzle with Geant4, but most of them can be useful for other Monte Carlo codes and passive scattering proton therapy treatment heads. Therefore, we consider this study useful for the use of Monte Carlo simulations with clinical applications.

Introduction

In this work, a Geant4 [1] application created to simulate the transport of protons through a passive scattering proton therapy nozzle has been analyzed with the purpose of improving its computational efficiency. The code reproduces the geometry of a real nozzle [2] and was validated prior to its use in the clinic. Now, we present our work in reducing the time needed to create the phase-space files that later are used to reproduce a given proton therapy treatment planning in a patient/phantom.

In general, the efficiency of a Monte Carlo simulation depends strongly on the complexity of the geometry, the physics models and the characteristics of the physics interactions defining the particle tracking through the materials. Since the “physics list” (in Geant4 argot, name given to the models used) was previously validated in this application [3], we focused our efforts in reducing the time by using geometrical aspects that usually are presented in every passive scattering proton therapy nozzle. Moreover, we have studied the time reduced by setting miscellaneous aspects of the Geant4 simulation, namely “production cut” value (minimum expected range of a secondary photon, electron or positron considered for tracking) and tracking of secondary particles, especially protons.

These techniques were tested using version 9.0-patch01 of Geant4 code. Another work using the latest version 9.3 is in progress. Preliminary results do not show dramatic differences on time with the results presented here, beyond intrinsic improvements in the efficiency of the Geant4 Monte Carlo toolkit.

Methods

The Geant4 collaboration provides a series of advices that any Geant4 application must fulfill in order to optimize the CPU performance [4]. They were already taken into consideration in the original version of this Geant4 code. Despite of following these tips, the CPU time of the Monte Carlo simulation to generate the phase-space files for patients is still too high compared with analytical techniques. According to this, we have developed other techniques, useful for passive scanning proton therapy nozzle simulations, that helps to reduce the time spent by the CPU. They are described below:

Proton analysis after the last scatterer module: once the protons come out of the last scatterer placed within the nozzle, they roughly follow a straight line towards the nozzle exit (snout). Hence, it can be predicted whether a particular proton will pass through the snout within certain tolerance margins. Fig. 1 shows 2-D histogram plots representing the distance between the position of the proton and central axis (radial coordinate) and the angle defined by the linear momentum direction and central axis (momentum \( \theta \) angle) for protons coming out of the last scatterer. In Fig. 1, left histogram counted all the protons passing the scatterer, whereas central and right plots represented only the protons arriving and not arriving to the phase-space plane, respectively. From this figures it can be determined that exists a correlation defining the protons reaching the nozzle exit.
Therefore, we recorded the current position and momentum direction of the protons coming out of the last scatterer, and the proton tracking was stopped if the projected line did not cross the snout aperture. We found that using a tolerance margin of 0.5 cm over the snout aperture was good enough to reproduce the original fluence at the exit. CPU time was reduced in all the cases analyzed. A ~5% reduction for the worst scenario of maximum size field (25-cm diameter snout) was achieved. Further, for a typical case (12-cm diameter snout) the CPU time was reduced in 25%–30%. As expected, the CPU time reduction depends on the field size: the smaller is the aperture, the more efficient is this technique.

**Simplified modelling of Ionization Chambers:** the geometrical model of a ionization chamber is usually composed by several thin layers of material (e.g. mylar or aluminium) and air. Although protons lose a very small percentage of their kinetic energy in the passage through ionization chambers, the Monte Carlo simulation becomes expensive in terms of time because of the navigation through this series of layers. In this situation, CPU time spent on the tracking through a ionization chamber can be reduced a 50% by just modeling all these layers as one unique layer which thickness is the sum of the actual layers thickness. This optimization contributes to reduce the overall CPU time in another 10%.

In addition, production cuts per region were defined. The modules composed of thick materials (range modulator wheel, first and second scatterer, aperture and range compensator) were left at the initial value (0.05 mm), since detailed tracking is mandatory in order to avoid a bias in the energy spectrum at the nozzle exit (Fig. 2). In the other hand, in modules that consist of delimited air gaps (like magnet modules, jaws and snout) the production cut value was increased (0.2 mm). However, this contributes in less than 5% to the reduction of time. Other aspects studied, like discarding the tracking of secondary protons, had a smaller impact on the time saved.

![Protons coming out of last scatterer](image1)
![Protons arriving to phase-space plane](image2)
![Protons after last scatterer not reaching phase-space plane](image3)

**Figure 1:** Left: scatter plot showing the correlation between the radial coordinate and the angle between the linear momentum and the central axis for protons coming out of the last scatterer. Middle: same contour plot representing the same coordinates after the last scatterer only for protons that reach the phase-space plane. Right: same contour plot presenting protons that do not reach the phase-space plane.

**Results and Discussion**

Fig. 3 presents comparisons of the time profiles obtained for the original and optimized code in a typical 12-cm diameter snout case (left) and a 25-cm diameter snout case (right). The most expensive modules in terms of CPU time (second ionization chamber and second scatterer) were marked for study, as shown in these plots. They demonstrate that the optimized Monte Carlo simulation becomes much more efficient than the original Monte Carlo for the tracking after the second scatterer. For our case, a 35% on the overall time is saved in the typical output factor case, whereas a 15% is saved in the maximum output factor case. As expected, this method becomes more efficient with smaller apertures and larger distance between the last scatterer and the nozzle exit.
Figure 2: Influence of the production cut value on the energy distribution of the protons crossing the phase-space plane at the nozzle exit. The settings of the machine were the same in all cases. A shift of approx. 1 MeV is observed between production cut value equal to 0.2 mm (black histogram) and production cut value equal to 0.05 mm (red histogram).

Figure 3: Comparison of the CPU time accumulated along the different modules of the nozzle. The original code profile is shown in red and the optimized profile is shown in green. Left: typical case of a 12-cm diameter snout. Right: maximum output factor case of a 25-cm diameter snout.

Regarding the influence that these techniques could have in the fluence at the nozzle exit, Fig. 4 shows the energy, radial distance to axis and angle aperture distributions of the protons at the phase-space plane for the original Monte Carlo code and the optimized version, respectively. The agreement is complete as seen from the residual plots.

We also clarify that the methods described in this work depend on the actual geometry of the passive scattering proton therapy nozzle, especially on the distance between the last scatterer and the nozzle exit. Hence, the results are valid only for our particular machine. However, these methods are applicable in Monte Carlo simulations of any other passive scattering proton therapy treatment head. Of course, the computational efficiency improvement will vary in terms of the geometry parameters. Therefore, we find that the results are useful for using Monte Carlo simulations in the clinics.
Figure 4: Example of fluence analysis in the phase-space plane to demonstrate the agreement between the original and the optimized code. This case corresponds to the analysis of the energy (left), radial (centre) and angular (right) distributions of a 114-MeV average kinetic energy beam. Residual plots are shown in the lower row.

References


