Kinetic energy of secondary fragments of $^{12}$C at varying incident energies in different biological media – A Monte Carlo study

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Abstract. This is a Monte Carlo study in GATE V8.0 investigating the nuclear fragmentation when $^{12}$C beams were incident at varying energies on different biological media. The researchers used one million monoenergetic pencil beam primary carbons irradiated to water, adipose tissue, skeletal muscle and cortical bone phantoms. The target was a box with dimensions of 20 cm x 20 cm x 20 cm to approximate the size of a human head. The energy was varied at 186.7 MeV/u, 241.7 MeV/u and 308.3 MeV/u. We obtained the number of the secondary particles produced in the fragmentation. We then chose the ten most abundant fragments and determined their kinetic energy distributions. $^{12}$C was most abundant in the fragmentation followed by proton. Either $^3$He or $^{11}$B had the least entries. The kinetic energy was inversely proportional to particles atomic number. In most cases proton and deuteron had the largest kinetic energy. The number of secondary particles increased with increasing incident energy. The kinetic energy had maximum increase at the stopping range, whose depth varied directly with incident energy and inversely with density of each material. The results were in agreement with the Bethe-Bloch formula.

1. Introduction

The development of carbon ion radiotherapy (CIRT) in Germany in 1997 has led the way to heavier ion therapy due to its many advantages compared to traditional techniques of light particle irradiation. Since then more operational centers have been established in many countries including Japan, Italy and South Korea [1].

From the standpoint of radiation biology, there is considerable rationale to support use of heavy-ions in treating cancer patients. This is because they exhibit defined Bragg peaks, which give maximum dose conformity [2, 5], Figure 1. This minimizes harmful radiation effect to the surrounding normal tissues. However, carbon-ions are heavier than protons and so provide a higher relative biological effectiveness (RBE), which increases with depth to reach the maximum at the end of the beam’s range [2, 5]. Thus the RBE of a carbon ion beam increases as the ions advance deeper into the...
tumor-lying region [2]. CIRT provides the highest linear energy transfer (LET) of any currently available form of clinical radiation [3, 5]. This high energy delivery to the tumor results in many double-strands DNA breaks which are very difficult for the tumor to repair. Conventional radiation produces principally single strand DNA breaks which can allow many of the tumor cells to survive [10]. The higher outright cell mortality produced by CIRT may also provide a clearer antigen signature to stimulate the patient’s immune system [4].

![Depth-dose profile of 12C ions (high Bragg peaks) and protons (low Bragg peaks) at varying incident energies where both had the same stopping range. Also shown in the profile the dose tail due to fragmentation of incident 12C [5, 6].](image)

Heavy ion particle therapy such as carbon has attractive radiation modality. However, the significant physical and biological effects they have deserve deeper investigation [5, 7, 8, 9]. The higher LET deliveries can still affect the healthy surrounding tissues as a result of nuclear fragmentation due to abrasion-ablation process [11, 12]. This effect is exhibited by the dose tail depicted in the depth-dose profile of incident 12C in Figure 1 [6, 11]. This phenomenon needs careful attention prior to clinical administration. The amount of dose deposition as well as the ionization process on the target and the surrounding normal tissues among others is crucial consideration [11]. These processes are directly related to the energy and the kind of the incident beam as well as the target material [5, 12, 13]. The number of particles scattered however is also important since the secondary particles produced may have a different biological effect to the healthy tissues [11]. Through this study the physics and the principles as well as other related knowledge on simulation activities can help better understand the processes taking place in heavy ion radiotherapy, particularly heavy ion 12C. For this reason, we would like to investigate the secondary particles produced during fragmentation by obtaining the number of secondary particles, rank them to 10 most abundant particles, and obtain the kinetic energy distributions of the 10 most abundant secondary particles.

2. Materials and Methods

In this Monte Carlo study, the researchers used one million monoenergetic pencil beam primary 12C irradiated at varying energies of 186.7 MeV/u, 241.7 MeV/u and 308.3 MeV/u from a distance of 1.0 cm on to water, adipose tissue, skeletal muscle and cortical bone phantoms. Each phantom was a box measuring 20 cm x 20 cm x 20 cm to approximate the size of a human head. We used GEANT4 version 10.3.2 simulation tools in GATE V8.0 to investigate the nuclear fragmentation by obtaining the secondary particles resulting in the interactions as well as the kinetic energy distributions of the 10 most abundant secondary particles. Figure 2 depicts the virtual target geometry and the visualized simulation.
Figure 2. Left picture shows the geometry of the virtual phantom while the right picture shows the entire virtual set-up during the simulation of beam irradiation.

3. Results and Discussion

Figures 3-6 below show the result of the simulations by materials. The top plots reveal the secondary fragments and the bottom plots show the corresponding average kinetic energy/5 mm bin size versus depth of the ten most abundant fragments. The energy was varied as 186.7 MeV/u, 241.7 MeV/u and 308.3 MeV/u respectively. The number of entries is indicated by the height of the histogram.

Figure 3. (Top) Histograms of the secondary particles for water. (Bottom) Kinetic energy distributions of the ten most abundant secondary particles.

For water phantom $^{12}$C had the largest count while $^{11}$B or $^3$He rank tenth. We observed that the number of secondary particles increased with incident energy. These particles were produced along the penetration length. The kinetic energy had maximum increase at the region of the stopping range (Bragg peak) in water and increased in depth with incident energy.
Figure 4. (Top) Histograms of the secondary particles for adipose tissue. (Bottom) Kinetic energy distributions of the ten most abundant secondary particles.

Similarly for adipose tissue the number of secondary particles increased with incident energy. $^{12}$C had the largest count while $^{11}$B and $^3$He rank tenth. These particles were produced along the penetration length. The kinetic energy also had maximum increase at the region of the stopping range (Bragg peak) and increased in depth with increasing incident energy. The stopping range of adipose closely resembled that of water.

Figure 5. (Top) Histograms of the secondary particles for skeletal muscle. (Bottom) Kinetic energy distributions of the ten most abundant secondary particles.

For skeletal muscle the number of secondary particles increased with incident energy. Likewise $^{12}$C had the largest count while $^{11}$B and $^3$He rank tenth. These particles were produced along the penetration length. Similarly the kinetic energy had maximum increase at the region of the stopping range (Bragg peak) and increased in depth with increasing incident energy. The stopping range of muscle is relatively smaller than that of adipose and water.
Figure 6. (Top) Histograms of the secondary particles for cortical bone. (Bottom) Kinetic energy distributions of the ten most abundant secondary particles.

For cortical bone the number of secondary particles also increased with increasing incident energy. $^{12}\text{C}$ and proton had the largest count while $^{11}\text{B}$ rank tenth. These particles were produced along the penetration length. The kinetic energy distribution had maximum increase at the region of the stopping range (Bragg peak) and increased in depth with increasing incident energy. The stopping range of cortical bone was lesser compared to that of the three previous biological media.

For reference purposes we present in figure 7 the absolute depth dose profiles of $^{12}\text{C}$ and proton beams taken from our previous work preceding these simulations. Here we determined the incident energies so that both $^{12}\text{C}$ (high peaks) and proton (low peaks) had the same stopping range.

Figure 7. Absolute depth-dose profiles showing the incident energies of both $^{12}\text{C}$ and proton, where both have the same stopping range in water, adipose, muscle and cortical bone phantoms respectively. Also shown here the Bragg peaks where the kinetic energy distributions underwent dramatic increase.

In the 12 histograms above, $^{12}\text{C}$ occupies the highest entries except in water and cortical bone when both incident with 241.7 MeV/u in which proton has the highest entry. The high count of $^{12}\text{C}$ is most likely attributed to the mix counts between the primary and secondary $^{12}\text{C}$, thus suggests further study to separate the primary carbon from the secondary carbon. Either $^3\text{He}$ or $^{11}\text{B}$ had the least entries. We observed that particles with small atomic number exhibit larger kinetic energy, which point to the fact that the square of the velocity far out weight the mass of the particles. Likewise particle with larger atomic number had lesser kinetic energy. In most cases either proton or deuteron had largest kinetic energy. Based on the histograms the number of secondary particles increases with increasing incident energy. Secondary fragments were observed along the penetration path and exhibit wide energy spectra [13]. When compared to previous the study of Figure 7, the kinetic energy exhibits increase at some defined range (Bragg peak) to some maxima, where the distributions almost constantly reached the edge of the target. The depth, where these dramatic increases were observed varies directly with incident energy and inversely with the density of material phantoms in agreement with the Bethe-Bloch formula.
4. Conclusion

The Monte Carlo simulations in GATE were performed. The secondary particles resulting from the passage of $^{12}$C ions incident at different energies in water, adipose tissue, skeletal muscle and cortical bone phantoms were revealed in histograms. The ten most abundant secondary particles were chosen and their kinetic energy distributions presented and analysed. The results were in agreement with the Bethe-Bloch formula.

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