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Simulation Study on the Feasibility of Using Heavier Ions in Charged Particle Therapy

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Proton therapy is a type of advanced radiotherapy that applies a high-energy proton beam to kill target cells by using the special physical properties of protons. In some institutes, instead of proton beams, carbon-ion beams are also utilized due to carbon ions having more ideal physical properties than protons. According to the interaction principle of particles of matter, a heavy ion, such as oxygen ions or heavier ions, could produce a sharper Bragg peak. In other words, heavy ions may show advantages in the dose distribution in comparison to protons or carbon ions. In order to confirm this, we used the Monte Carlo method to simulate the radiotherapy using various heavy ions, and we calculated the dose in the target volume and the normal volumes. The results show that the heavier ion will deposit a higher energy the target volume in the case of the same dose deposition in the normal volumes. In conclusion, in particle radiotherapy, a heavier ion could provide a more ideal physical dose distribution compared to those of protons and carbon.

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I. INTRODUCTION

Proton therapy is a kind of advanced radiation therapy using the advantage of proton therapy that the release of bulk proton kinetic energy can be controlled. In proton therapy, as the protons move through the body, they slow down and interact with electrons, and release energy. The point where the highest energy release occurs is the position of the Bragg peak. A physician can designate the Bragg peak's location, causing the most damage to the targeted volume and sparing healthy tissues and organs [1–3].

Carbon ion is another kind of radiation therapy that utilizes carbon ions instead of protons to destroy the target. Due to the physical characteristics of a carbon ion beam, for example lower oxygen enhancement ratio (OER) and higher relative biological effects (RBE) than proton therapy, carbon ion therapy is better in dose delivery, sparing healthy organs at risk and good performance for oxygen deficient tumors such as in the head and neck [4,5]. The two main significant dose distributional differences between proton and carbon ion beam therapies are that carbon ion beams have narrower penumbras and have fragmentation tails. There is another highly important additional difference between the two beams: proton beams are low linear energy transfer

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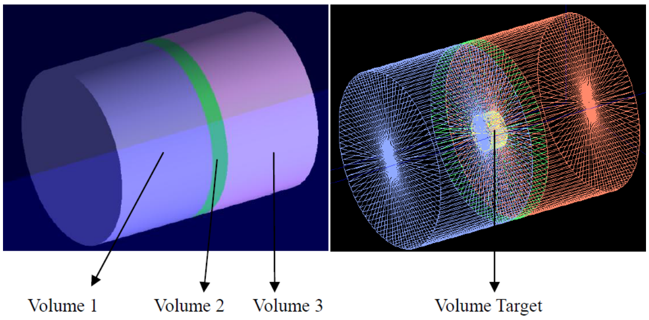

Fig. 1. (Color online) The visualization of geometry in simulation. Volumes 1, 2 and 3 are normal volumes surrounding the target volume that located at the center of volume 2.

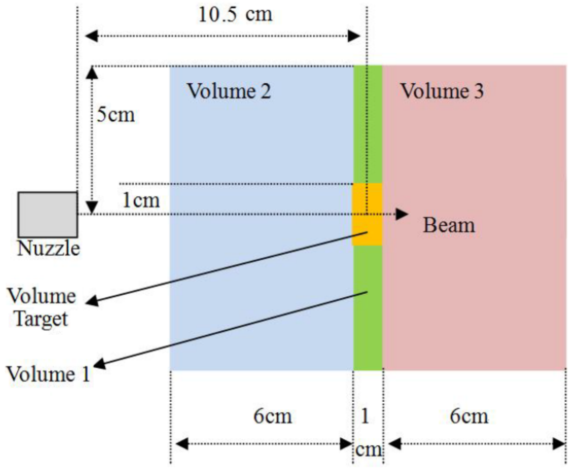

Fig. 2. (Color online) The scheme diagram of cross section of geometry in simulation experiment.

(LET) and carbon ion beams are high LET. The potential gain from the high LET and high RBE characteristics of carbon ion irradiation may principally be due to a lower and perhaps a smaller variation in radiation sensitivity with the position of the cells in the cell replication cycle [6–9].

Modern clinical accelerators are capable of producing ion beams from protons up to heavy ion beams. This makes ion beam therapy using heavier ions possible. However, there are not many studies reported about the heavy ion therapy method using an ion beam heavier than the carbon ion. In order to analyze the feasibility of heavy ion therapy using an ion beam heavier than proton and carbon, in this study, we apply the Monte Carlo method to simulate the particle therapy process and discuss the feasibility of usage of heavier ion beams in radiation therapy.

Table 1. The energy of various ions when their mean ranges are 10.5 cm.

Ion	p	C	N	O	F	Na	Al	P	Cl	Ca	Fe
Energy	125	233	263	281	295	343	388	403	443	500	517

Note: the unit of energy is MeV/u.

II. SIMULATION METHOD

1. Simulation Contents

The goal of radiation therapy is to deliver a higher radiation dose to the target and lead to lower radiation dose to normal tissues. Therefore, the dose distribution of radiation in the body is the most important factor used to evaluate the therapy effect. In order to evaluate the distribution of dose in the target volume and various surrounding normal tissue volumes, in this study we developed a simulation experiment as shown in Fig. 1 and 2.

In the simulation we will analyze the doses of target volume and three normal volumes of various heavy ion beams. All volumes have the geometry of a cylinder and the target volume is located at the center of the whole geometry. The target volume is the target. The volume 1, volume 2 and volume 3 are normal tissues. The sizes of all volumes are shown is Fig. 2. In radiotherapy, the dose of volumes in front of target, surround the target and behind target are used to evaluate the therapy effects. Therefore we divide the normal tissue into 3 volumes. The volume 1 locates in front of target, the volume 2 surrounds the target, and the volume 3 locates behind of target. In simulation the Bragg Peak is set to occur at the center of the target volume, and the distance of the Bragg Peak point to the nuzzle is 10.5 cm. The materials of target volume and volumes 1, 2 and 3 are set with tissues, and the material of the other volumes is set as water.

2. The Ion Beam and Energy of Ions

For ion beams, besides the referred beams: proton and carbon ion, we will analyze the dose distribution of the beams of the nitrogen ion, oxygen ion, fluoride

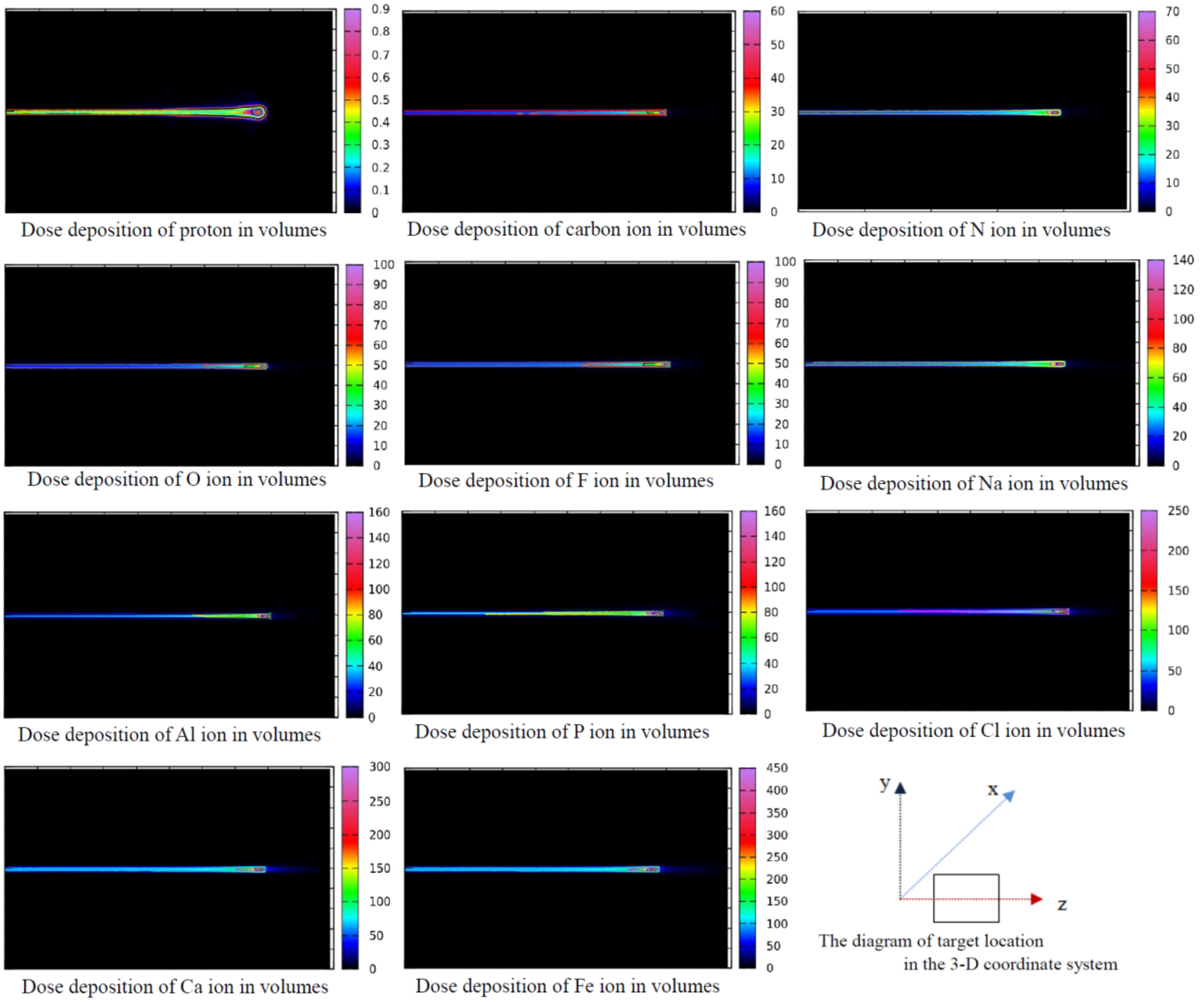

Fig. 3. (Color online) The dose deposition in all volumes as a 2-D plot. The ion beam is ejected from coordinate origin and pass through the volumes along the z-axis direction.

ion, sodium ion, aluminum ion, phosphorus ion, chloride ion, calcium ion and iron ions.

Considering the difference in mean ranges of various ion beams, we utilized the Stopping and Range of Ions in Matter (SRIM) program to calculate the energy of all types of ion beams when their mean ranges were 10.5 cm in water and in soft tissue (from nuzzle to center of target volume). The simulation results are shown in Table 1.

In this study, we define the total dose deposition in the target volume is 1 Gy for all types of ions. Under this definition, we will count the dose deposition of volumes 1, 2 and 3, and analyze the output results.

III. RESULTS AND ANALYSIS

In simulation, GEANT4 low energy electromagnetic physics processes were used for all ions. A water phantom consisting of 3000 packed rectangular detector sheets was used in this simulation. A 1 mm diameter pencil beam of various ions was used in all simulations presented. The beam is ejected from the coordinate origin point and move along the direction of z-axis. The total dose of each ion beam in each volume is accumulated. The simulation result about physical dose as a function of depth was calculated and outputted in Fig. 3.

Table 2. The dose deposition in normal and target volumes.

Ion	p	C	N	O	F	Na	Al	P	Cl	Ca	Fe
Target Volume	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Volume 1	0.312	0.310	0.291	0.287	0.221	0.201	0.170	0.140	0.121	0.100	0.091
Volume 2	0.031	0.029	0.028	0.026	0.025	0.023	0.021	0.020	0.019	0.016	0.015
Volume 3	0.043	0.090	0.100	0.121	0.131	0.146	0.156	0.178	0.190	0.210	0.230

The unit of dose is Gy.

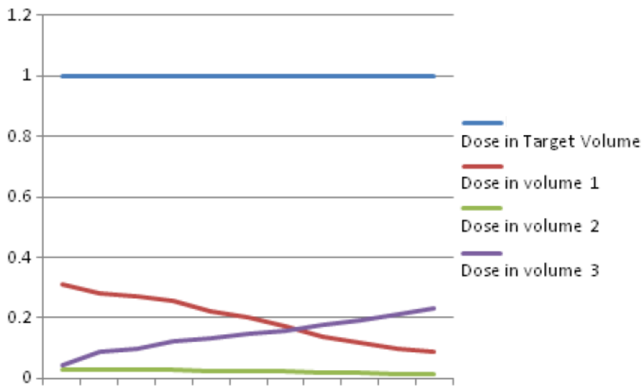

Fig. 4. (Color online) The change of dose in the target volume, and volumes 1, 2 and 3 when the incident ion became heavier.

In order to analyze the characteristics of dose deposition in various volumes, besides the above dose deposition plots, the simulation results are shown in Table 2. For visualization of the results of Table 3, the results can be shown in Fig. 4.

Through analysis of simulation results about Fig. 3, Table 2 and Fig. 4, the following conclusions can be found.

1. The dose of volume 1 decreases with the increase of ion mass. Therefore, when the important organs are located at the just front of the target, heavier ion beam therapy is advantageous. This proves that relative to proton and carbon ion beams, heavier ion beams provide superior distributions of dose.

2. The dose of volume 2 surrounding the target also decreases with the ion mass increase. This also shows the heavier ion beams may have advantages in physical dose distribution relative to proton and carbon ion beams.

3. The dose enhancement of volume 3 shows a big difference in dose distribution between 1H, 12C and heavier ion beams due to the fragmentation tail of the ion beam. The tail develops from the fragmentation of the heavy ions in the primary ion beam, due to their nuclear interactions with the atoms in the irradiated medium. Some of these fragments travel non-negligible distances beyond the range of the primary ion beam and deposit their dose in the "fragmentation tail".

In conclusion, the dose distribution results suggest more effectiveness of dose distribution in the target volume for heavier ions compared to proton and carbon ion therapy. In clinical application, this makes the heavier ion beam therapy have a more ideal dose deposition and cause a lower dose into the surrounding normal tissues and organ.

IV. CONCLUSIONS

The purpose of this investigation was to reveal the dosimetric characteristics of various ion beams heavier than proton and carbon ions in water and tissues. The depth dose distribution of different ions of interest has been investigated using the Monte Carlo code Geant4. In this study we compared the depth dose distribution of various ion beams in designed volumes. Through analyzing the simulation results, it can be concluded that the heavier ion beam presents superior physical depth dose distributions relative to the proton or carbon ion beam. Considering in particular application, except the physical dose, the RBE values of various ions measured by radiation biology experiment is also important in evaluation of the radiotherapy effects. Therefore, in future studies, we will corporate with a radiobiology group and combine the analysis of both physical and biological dose of heavy ion beams.

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