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An Investigation of Muon Therapy

Jong-Kwan Woo · Dong Liu*
Department of Physics, Jeju National University, Jeju 63243, Korea
BK21plus Clean Energy Convergence and Integration Center for Human
Resources Training and Education, Jeju National University, Jeju 63243, Korea

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The muon is a subatomic particle that includes the positive and negative muon with a charge of −1 and 1, respectively. For the mass, the muon is heavier than the electron. As for a proton beam, the muon beam shows a Bragg peak when it interacts with materials. Therefore, the muon beam, as well as the proton beam, can also be considered as a candidate for radiotherapy. In this study, based on the Monte Carlo method, we defined a water phantom that which included a target volume and three interesting volumes. Then, the interaction processes of proton, positive and negative muon beams in materials were simulated. Moreover, the dose depositions of proton beam, positive and negative muon beams in each volume were calculated. An analysis of the calculated results, showed that compared to a proton beam, especially the negative muon beam, had an advantage in reducing the physical dose deposition in the upstream volume of the target.

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I. INTRODUCTION

The proton therapy is the mostly widely used particle therapy method, benefits from the dose distribution of Brag peak [1–4]. Besides of proton, the other charged particles, which have the similar dose distribution with proton, are also can be considered as the candidates of particle therapy methods. As we know that the muon (μ^+ and μ^-) may create the Bragg peak when it passes through the materials. In another word, the muon can deposit the less dose in the health tissues, and deposits the most dose in the target. Therefore, in principle, the muon is also can be considered as the candidate of particle therapy [5].

In this study, in order to analyze the dose distribution, and to evaluate the possibility of medical application of muon beam, based on the Monte Carlo method, the interaction processes of muon beam with materials will be simulated, and the dose distribution of muon beam will be calculated. Accordingly, the therapy effects of muon beam will be evaluated. For comparison, the dose distribution of proton beam is also calculated.

II. SIMULATION DETAILS

For simulation, the Particle and Heavy Ion Transport code System (PHITS) program is used to simulate the interaction processes of three kinds of beams (μ^-, μ^+, and proton) and materials. The PHITS is a general purpose Monte Carlo particle transport simulation code, which can be used to simulate the transport of all particles over wide energy ranges, using several nuclear reaction models and nuclear data libraries.

1. Geometry Definition

The geometry of phantom is combined with 4 volumes that shown in Fig. 1, the volume 4 is the target volume, which is located in the center of the three volumes of interest. For the three volumes of interest, the volume

*E-mail: liudongcn@jejunu.ac.kr

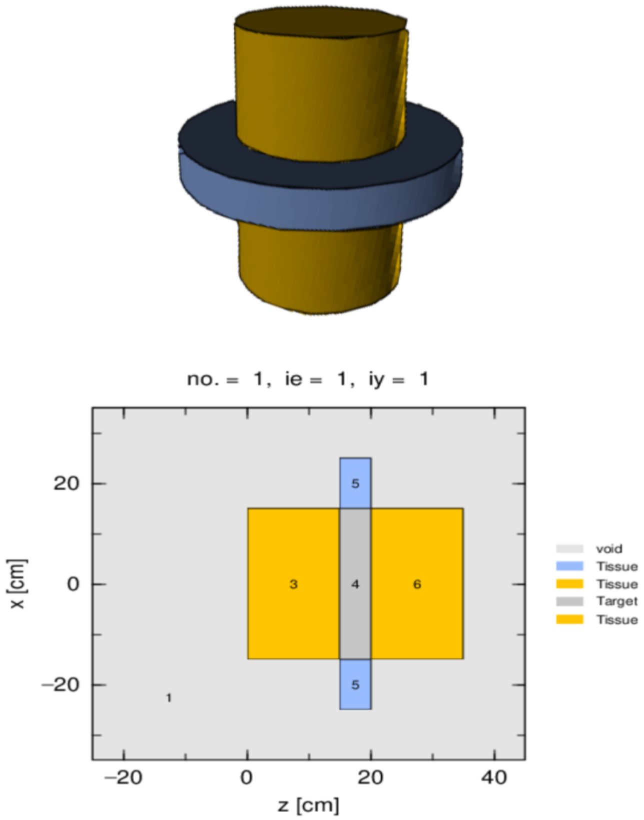


Fig. 1. (Color online) The visualization of geometries. There are four volumes in the phantom, which includes proximal volume, lateral volume, distal volume and the target volume. In simulation, the three volumes of interest and the target volume are irradiated by using specified beams of proton, μ^+ and μ^-.

Table 1. The parameters of 4 volumes.

Volume	Proximal Volume (Volume 3)	Lateral Volume (Volume 5)	Distal Volume (Volume 6)	Target Volume (Volume 4)
Shape	Cylinder	Hollow Cylinder	Cylinder	Cylinder
Radius	15 cm	15 cm/25 cm	15 cm	15 cm
Length	15 cm	5 cm	15 cm	5 cm
Volume	10597.5 cm^3	3532 cm^3	6280 cm^3	10597.5 cm^3

3 is ‘proximal volume’, the volume 5 is ‘lateral volume’, and the volume 6 is ‘distal volume’. The materials of all volumes are assigned to tissues [6,7]. The geometric parameters of above 4 volumes are shown in Table 1.

2. Beam Parameters

In the simulation, the incident beam is assigned to firstly penetrate the proximal volume then toward the

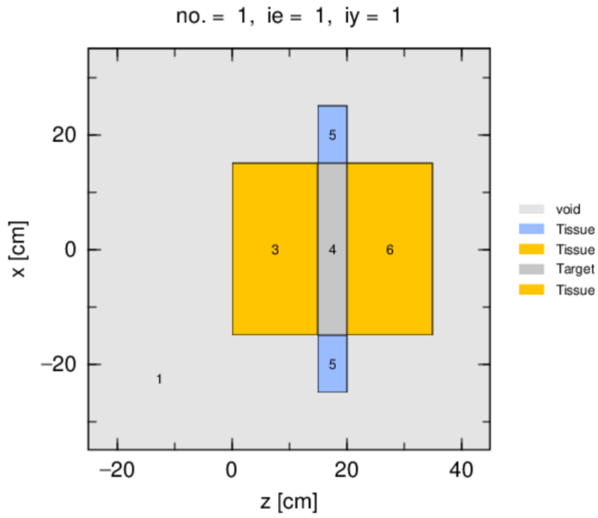


Fig. 2. (Color online) Illustration of the beam direction. The beams firstly penetrate the volume 3 (proximal volume) and toward to volume 6 (distal volume), and create the Bragg peak in the center of the volume 4 (target volume).

Table 2. The parameters of the proton, μ^+ and μ^- beams.

Radiation	Proton	Muon+	Muon−
Energy	159 MeV	70 MeV	70 MeV
Range	17.5 cm	17.5 cm	17.5 cm
Beam Shape	Cylinder Beam	Cylinder Beam	Cylinder Beam

distal volume as shown in Fig. 2. To deposit the dose mostly (Bragg peak region) in the center of target volume, the energy of various beams are calculated and are summarized in the Table 2. The radius of cylinder beam is 15 cm.

III. RESULTS AND ANALYSIS

Through taking the simulated calculation, the dose-depth curves of various beams, the tracks of various beams and the dose deposition distribution in the form of 2-demontion of various beams are obtained. In addition, the dose values of various beams in each volume are also calculated and are summarized in Table 4. In order to compare the dose deposition of various beams, the ratio of dose in other volume to the dose in target volume are calculated and shown in the Table 3.

The dose-depth curves of various beams are shown in Fig. 3, which exhibits distinct differences in a peak-to-plateau ratio and the sharpness of the Bragg peak for

Table 3. The dose deposition into volumes for opposite field beams (Gy).

	Dose in Proximal Volume	Dose in Lateral Volume	Dose in Distal Volume	Dose in Target Volume
Proton	1.4679E-06 (82.139%)	4.0639E-10 (0.0227%)	2.9435E-09 (0.166%)	1.7871E-06 (100%)
Muon+	7.1035E-07 (50.603%)	2.3376E-08 (1.664%)	1.0978E-07 (7.818%)	1.4044E-06 (100%)
Muon−	7.1153E-07 (50.405%)	1.3331E-08 (0.971%)	9.2739E-08 (6.473%)	1.4125E-06 (100%)

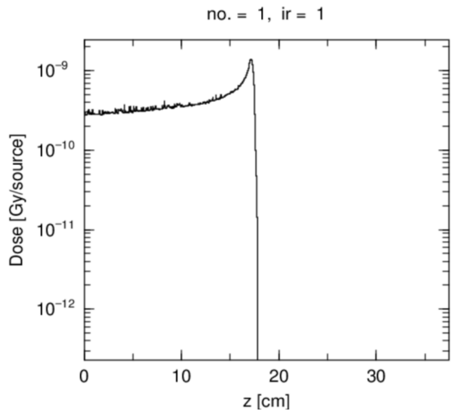
each beam. It can be seen that the proton shown a less tail effect behind the volume 4, compare to the two kinds of muon beams. That means the proton makes less dose deposition in the volume 6 compare to muon beams.

The tracks of various beams are shown in Fig. 4. In which, it can be seen that for muon beams, the big amount of tracks is shown in the outside region of volumes 4. However, for proton only a small amount of that is shown in the outside region of volume 4. The reason of this is that muon beams create the more secondary particles compare to proton. This may explain that the Bragg peak of proton is sharpness compare to that of muon beams.

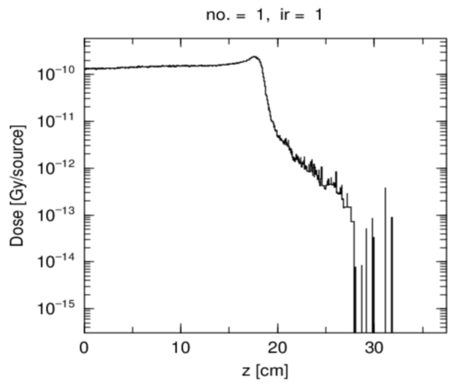
The dose deposition distribution in the form of 2-dimension of various beams is shown in Fig. 5. In which, it can be more clearly seen that the proton majorly deposit dose into the volume of 4 and 3. However, for muon beams, some dose is deposited to the volume of 5 and 6, and the μ^+ deposits more dose to volume 5 compare to μ^-.

Through analyzing above three figures about the tracks and dose distributions of various beams, it can be seen that compare to proton, the muon beams do not have some clear advantages. Then we will evaluate dose deposition value in the four kinds of volume that shown in table 3.

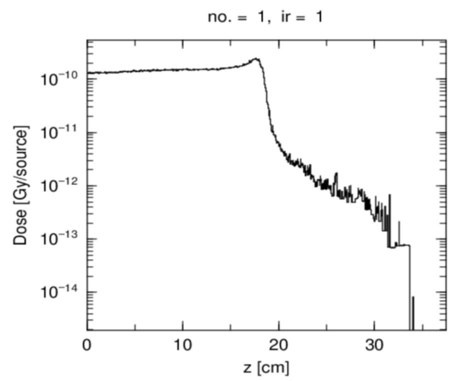
Through analyzing the dose deposition in various volumes, it can be found that when the dose deposition in the target volume is set as 100% dose, then the dose deposition of in the proximal volume for μ^+ and μ^- is lower than that of the protons, and the μ^- is less than the μ^+. However, for the dose of the distal volume behind the target volume and lateral volume that surrounding target volume, less dose is deposited by the protons.



(a) The dose-depth curve of the proton.



(b) The dose-depth curve of the μ^+ beam.

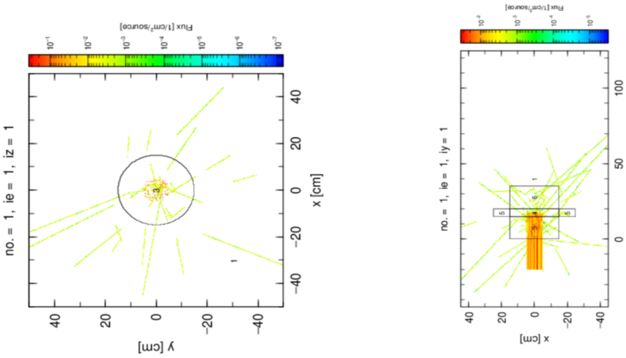


(c) The dose-depth curve of the μ^- beam.

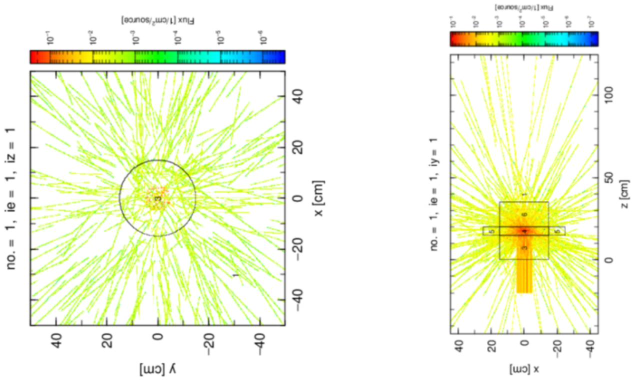
Fig. 3. The dose-depth curves for each kinds of beam.

As for the dose deposition of μ^+ and μ^- beams, it can be seen that they are very similar. However, the μ^- beam deposits the less dose to the proximal volume, lateral volume and distal volume, compared to μ^+. Especially, μ^- beam causes the almost half dose deposition in lateral volume, compared to μ^+, which mainly due to the interaction processes of μ^- with materials.

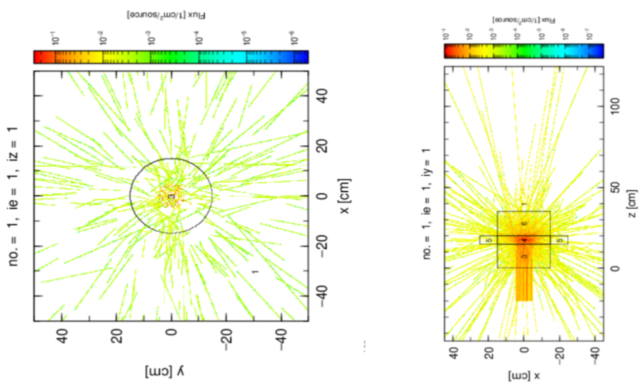
In summary, the μ^+ and μ^- beam may deposit lower dose in the proximal volume, compared to the proton



(a) The track of proton beams

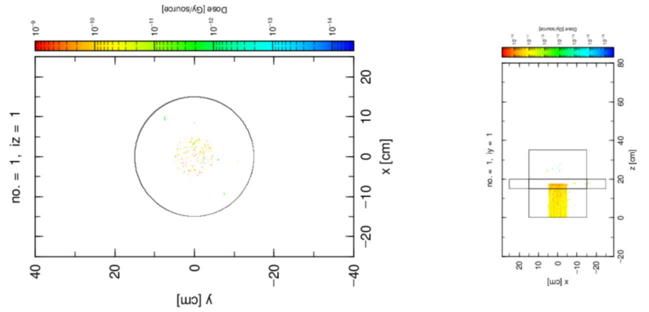


(b) The track of μ^+ beams

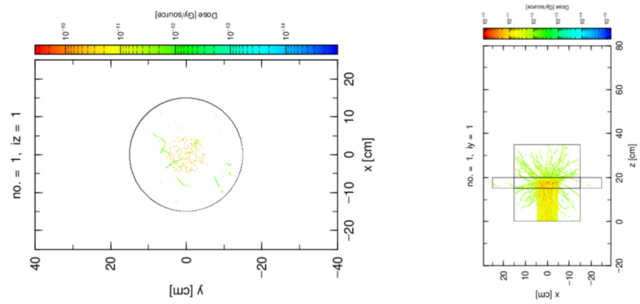


(c) The track of μ^- beams

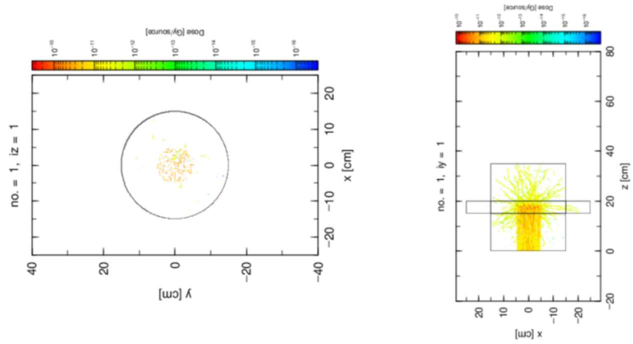
Fig. 4. (Color online) The tracks of the three kinds of beams in each volume.



(a) Dose distribution of proton beams



(b) Dose distribution of μ^+ beams



(c) Dose distribution of μ^- beams

Fig. 5. (Color online) The dose distribution of various beams in each volume.

beam. Therefore, for the case that lower dose has to be deposited in upstream of target volume, the μ^+ and μ^- beams have advantage. Moreover, considering the less dose deposition in three volumes of interest, especially in lateral volume, the μ^- is more ideal as the candidate of particle rather than μ^-.

IV. CONCLUSIONS

In this study, through simulate the interaction processes of three kinds of beams and tissues materials, and analyze the dose deposition of such beams in the target volumes and three volumes of interest, it can be found that as the charged particle, muon beam may creates the Bragg peak in dose deposition when it penetrate the materials. Therefore, the muon beam deposits the less dose in the proximal volume, lateral volume, and lateral volume, and deposit the more dose in the volume of target.

In addition, compared to the proton therapy, the muon creates less dose in the proximal volume. Therefore, in conclusion, compared to the proton beam, the muon beam has its advantage, especially in the case that lower dose deposition in the proximal volume has more precedence, comparatively speaking. Furthermore, for the two muon beams, the μ^- deposits the less dose in three volumes of interest, especially in lateral volume. Therefore, compared to the μ^+, the μ^- is more suitable as the candidate of particle therapy beams.

In this study, only the physical aspect of the proton and muons are considered, for the future study, the biological dose will be considered as well as the physical dose.

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