Original

Investigation the Performance Accuracy of Contoured Dual Ring Double Scatterer System for Flat Beam Generation at Proton Therapy

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ABSTRACT

Background: At proton radiotherapy, the extracted beam from accelerator is not initially suitable for tumor treatment and a modification is needed for beam shape and energy due to tumor dimension and site. One clinical strategy is the use of double scattering systems known as passive dose delivery technique to generate proper flattening, transversely.

Objective: This work aims to design and simulate a new version of double scattering system and compare its performance with another available scatterer system, quantitatively.

Material and Methods: In this analytical study, Monte Carlo FLUKA code is utilized to simulate the performance of proposed system in generating lateral flat beam. The simulation process is very close to real experimental condition, performed at proton beam irradiation room at Tohoku University in Japan. Moreover, the presence of secondary neutrons, produced due to protons collision with proposed scattering system, is considered as main issue.

Results: Final results represent that the proposed scattering system is robust to generate 40 mm flat region with an acceptable uniformity degree. Energy loss caused by current dual scatterer is more than simple ring technique, while the secondary neutrons produced by proposed system are larger than other system.

Conclusion: This study simulates the performance of a new dual ring double scattering system. Final results show that there is a close correlation between proposed system and current scattering system. The only concern is about the presence of secondary neutrons mainly at high energy proton particles.

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Keywords

Proton Therapy; Scattering; Radiation; Proton Beam; Neutrons; Monte Carlo Method

Introduction

In recent years, proton beam has been recognized as effective therapeutic beam for cancer treatment due to its Bragg curve properties, resulting the significant damage onto cancerous cells and keeping normal tissues safe against additional high dose, especially for Organ at Risk (OAR) located at beyond the tumor [1-4]. This strategy is accordingly implemented mainly for tumors located at deep parts of patient

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body. In general, the implementation of radiotherapy consists of two main components: 1) tumor delineation and localization, 2) beam line preparation and prescribed dose delivery. The latter component is highly important while the therapeutic beam must be aligned with tumor volume as well [5-9].

In fact, at proton radiotherapy, the pencil beam extracted from accelerator exit window is not applicable in its initial form and the beam shape and energy must be modified by means of appropriate instruments to spread proton particles according to tumor lateral size and to shift beam range based on tumor position. In other word, these devices are responsible to provide 3D uniform dose onto tumor volume transversely and in depth versus beam emitting direction. To do this, there are two common available delivery strategies known as active and passive techniques [9-19].

In active or spot scanning techniques, the pencil beam is directly employed to deliver uniform dose onto tumor volume, three dimensionally. For this aim, an available beam wobbler system, including dual magnets is implemented to deflect the beam direction horizontally and vertically sweep it across the tumor, layer by layer against beam propagation [10]. During treatment planning process, the tumor volume is assumed to be divided into several virtual layers. Then, each layer is swept by pencil beam from distal part to proximal part of tumor versus beam propagation direction. By this strategy, the total volume of tumor receives the uniform prescribed dose, three-dimensionally. It should be noted that transferring the Bragg peak from one virtual layer to the next layer is performed using proper range shifter with pre-defined thicknesses made by plastics. Moreover, in this technique, the beam irradiation time of proton beam at each spot is variable and calculated using treatment planning computer systems to finally result 3D uniform dose throughout tumor volume [11-13].

In passive technique, the required passive tools are placed in front of therapeutic proton beam between exit window and patient body in order to provide proper 3D uniformity at both longitudinal and lateral directions [14-16]. Since, passive beam delivery technique is applicable clinically; designing and investigating the performance of scattering systems are still considered as challenging issue.

For longitudinal uniformity, the therapeutic beam must be modulated in depth using Spread out Bragg Peak (SOBP) technique. One of most common available passive tool for this aim is ridge filters that can be constructed at different shapes and dimensions [16]. By this method, proper uniformity is obtained to cover tumor volume in depth direction.

Apart from SOBP and longitudinal treatment region, for lateral flattening, the narrow pencil beam is firstly broadened and then is converted to uniform beam (with reasonable flattening degree) by means of passive devices, dedicated for this aim [17-21]. This uniform beam provides lateral treatment region and finally is collimated according to transverse dimension of each tumor, on a case by case basis. In practical, two techniques are implemented to make proper flattering in transverse direction perpendicular to beam propagation: 1) using single scatterer in combination with beam wobbling system 2) using double scatterers technique. The latter case is sub-divided into two methods: 1) Contoured Double Scatterers and 2) Ring Based Double Scatterers.

Several research works have been done on the performance of various instruments for providing lateral flattening regions, ranging from their designs to simulations and fabrications. At our last work, a comprehensive assessment was done on the design and fabricating a contoured compact dual scatterers applicable at Rotating Gantry system in Cyclotron and Radioisotope Center (CYRIC) at Tohoku University in Japan [20-22]. In this work, we are interested to design and simulate another version of scattering system entitled dual ring double scatterer as an alternative to be implemented for proton beam line. Therefore, there is a major requirement to quantitatively investigate the physical properties of this instrument ranging from secondary's produced by irradiating primary beam to its performance accuracy in the frame of a comparative study with contoured double scatterer. In this work, we assessed the performance of both double scattering systems, comprehensively taking into account the advantages and weakness points of each system while no evaluation has been done for a long time of period.

Due to this lack of information, our main focus in this work is on the concept of lateral uniformity provided by passive beam delivery strategy, comprehensively. We investigate the length of flat treatment region that must cover tumor volume in its transverse direction with proper uniformity degree. Furthermore, the energy loss of protons caused by scattering systems is also attractive to be investigated. By inserting scattering systems in front of beam line in proton therapy, due to the interaction of protons with different components of scattering system, some concerns raise due to high energy secondary neutrons that must be taken into account, seriously in the context of whole body dose. Therefore, secondary neutrons produced by this scattering system are considered as one of the main challenging issues in this work [23-24].

To do these aims, a validated Monte Carlo FLUKA code is utilized to simulate the performance of proposed double scattering system [25-30]. It should be noted that the simulation process is very close to real experimental condition at proton beam room in CYRIC center at Tohoku University in Japan to mimic real condition [20-22] and final results represent that the scattering system is robust to generate flat region in lateral direction.

Material and Methods

This analytical study illustrates the performance of new proposed double scattering system by considering to another available scattering strategy, in a comparative study.

Single scatterer with wobbling system

While irradiating using horizontal beam line, lateral homogeneous dose is generated using two common strategies: 1) single scatterer with wobbling system 2) double scatterers. Figure 1 shows a schematic layout of wobbling system in combination with single scatterer for flat beam generation. As seen in the Figure 1, two magnets are employed to deflect pencil beam to each given position. Then, a thin foil made by metal with high atomic number acts as scatterer to finally produce flat beam. Finally, a collimating system is implemented to stop peripheral protons distributed non-uniformly around flat treatment region.

Double scattering systems

In the second strategy, double scattering system includes two scattering sub-systems. This system can be fabricated in two basic methods which are: 1) compensated contoured double scattering methods (Figure 2, upper part) and 2) dual ring double scattering (Figure 2, lower part) methods.

The upper part shown is the Figure 2 was assessed formerly at our last study [22]. In this study, we investigate lower strategy using FLUKA code and the final results of its perfor-

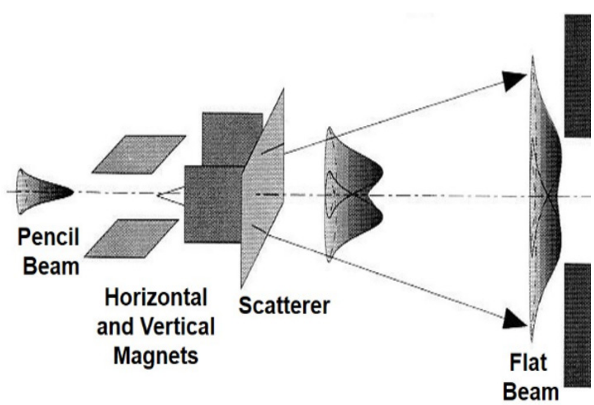

Figure 1: A schematic layout of single scatterer with wobbler system.

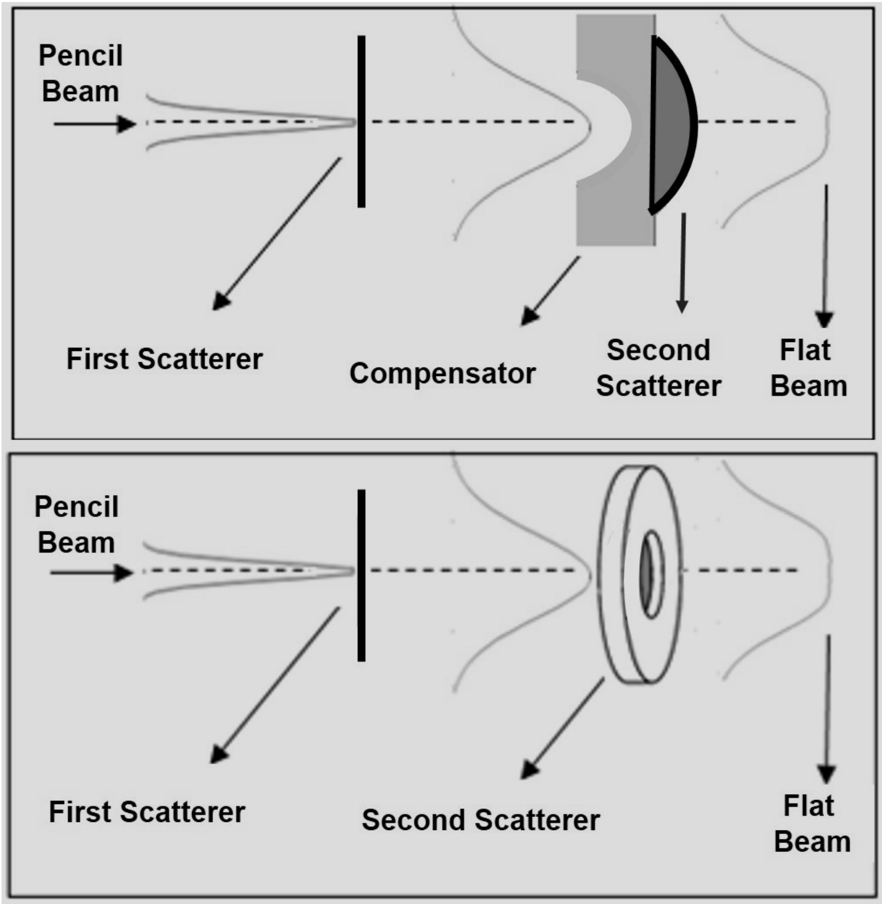

Figure 2: Schematic layout of contoured double scatterer (upper part) and dual ring double scatterer (lower part).

mance were compared with contoured double scatterres method, quantitatively.

While protons leave the first scatterer, they are spread in a specific range of angles because of multiple coulomb scattering effect in interaction of charged particles with thin matters [23]. It should be noted that the spatial distribution of protons are as Gaussian with specific Full Width at Half Maximum (FWHM) after crossing first scatterer.

The second scatterer of double scattering system (Figure 2, upper part) has been made by high Z (atomic number) metal, in 3D cone shape. Due to this shape, its scattering strength is variable and reduces from its central inner part toward its peripheral outer parts. Therefore, various spatial Gaussian distributions of protons with different FWHMs are emerged after passing the second scatterer and the sum of total Gaussian distributions results flat beam with acceptable uniform treatment region to cover lateral side of target volume. It should be noted that the second scatterer at double scattering system has different effects on energy loss of protons due to its cone shape. The maximum energy loss will be happened for protons passing from the central past of second scatterer, where the thickness is maximum. In order to address this issue, an energy compensator with variable thicknesses has located just before second scatterer to cause constant energy loss for all protons leaving this system (Figure 2, upper panel).

Dual ring double scatterer system (Figure 2, lower panel) and the second scatterer include two inner and outer rings with different diameters, made by heavy (high atomic number or Z) and light metals (low atomic number or Z), respectively.

In this system, protons are firstly broadened after passing the first scatterer. While protons reach the second layer, they will broaden with different scattering degrees due to different thicknesses of this layer. For example, protons that are closer to the central beam axis scatter remarkably because of crossing from the maximum thickness of the second scatterer. In contrast, protons that are far away from the central beam axis scatter fewer due to the reduction of the scatterer thickness at its peripheral part. Therefore, various 3D Gaussian functions represent protons spatial distribution behind the scattering system and the sum of these functions result proper 3D uniformity. Then the total spatial distributions of all central and peripheral protons may cause flat beam with uniform treatment region.

From computational point of view, the fluence at each point on measuring plate depends on a scatter event through the first scatterer to a point on the second scatterer and then another scatter event from that point on the second scatterer to a point on the measuring plate, integrated for all points on second scatterer.

Simulation setup

In this work, Monte Carlo FLUKA code has been used for simulating two scattering systems by considering all parameters during geometry and material definitions to mimic real condition. The FLUKA is a well-established validated code that has found various uses in different fields [25-30].

In our simulation, Lead metal was used as the first and second scatterers material at both strategies due to its high density (11.34 gr/cm^3) and Polymethyl methacrylate (PMMA) was used as compensator material because of its low density (1.19 gr/cm^3) to attenuate the protons energy without spreading them at double scattering strategy.

The thickness of the first scatterer and thickest part of the second scatterer are 1.25 mm and 1.33 mm in contoured double scatterer system. In dual ring scattering system, the thickness of the inner (Lead) and outer (Aluminum) rings are 2.58 mm and 5.27 mm, respectively. The distance between the first and second scatterers at both strategies are 100 mm which is a robust point and can save enough space for using other required passive devices (e.g. range shifter) between beam exit window and target. Taking into account protons as therapeutic beam, one of the main challenging issues is secondary neutrons produced due to interaction of protons as incidence particles with all passive or active devices located in front of the proton beam and also inside patients body (at real treatment) or phantoms at research activities. Since we are focusing on the performance of scattering systems as an important instrument in proton beam, there is a need to consider secondary neutrons. For this aim and apart from flat beam generation assessment, FLUKA code is also utilized to measure produced neutrons due to protons interaction with both scattering systems components ranging from first scatterer to compensator and second scatterer.

Results

Figure 3 shows the Bragg peak profiles resulted from 1) contoured double scattering (solid line) and dual ring double scattering system (dashed line) inside water tank by simulating 80 MeV proton beam line. As seen, there is 5 mm difference between two obtained depth dose profiles that is due to further energy loss of dual ring double scatterer versus contoured double scatterer system. It's worth mentioning that the thickness of second scatterer at both scattering systems has non-negligible effect of the energy of proton particles that may shift the peak of Bragg curve to the left side.

It should be considered that the total thicknesses of first and second scatterers at contoured double scattering and dual ring double scattering systems may cause 5 MeV and 10 MeV energy loss (over 80 MeV as energy of protons), respectively.

It should be noted that the Bragg peak curve obtained by simulation method has close correlation with same curve obtained experimentally using Imaging Plate at our last research work [22].

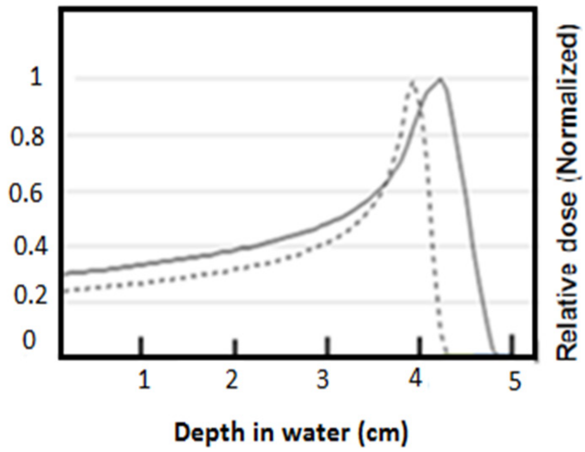

Figure 3: Depth dose profiles of contoured double scatterer (Solid line) and dual ring double scatterer (Dashed line)

Figure 4 represents flat beam profile generated by dual ring double scatterer (solid line) in comparison with same result from double scatterer system (dashed line) by simulating 80 MeV proton beam line or X axis. The dimensions of produced flat beam representing treatment region are 38 mm and 40 mm for double scatterer and dual ring double scattering systems, respectively. The same results have been achieved on Y axis. Moreover, the initial beam extracted from exit window of cyclotron machine has been considered as 3D Gaussian shape with FWHM same as real condition, during simulation process.

As mentioned, scattered neutrons were produced while interacting proton beam with two scattering systems was considered in this work. At a glance, the produced neutrons at both systems are almost same, but total neutrons produced at dual ring double scatterer are approximately 10% larger than the same result produced during simulating contoured double scatterer. This is due to more interac-

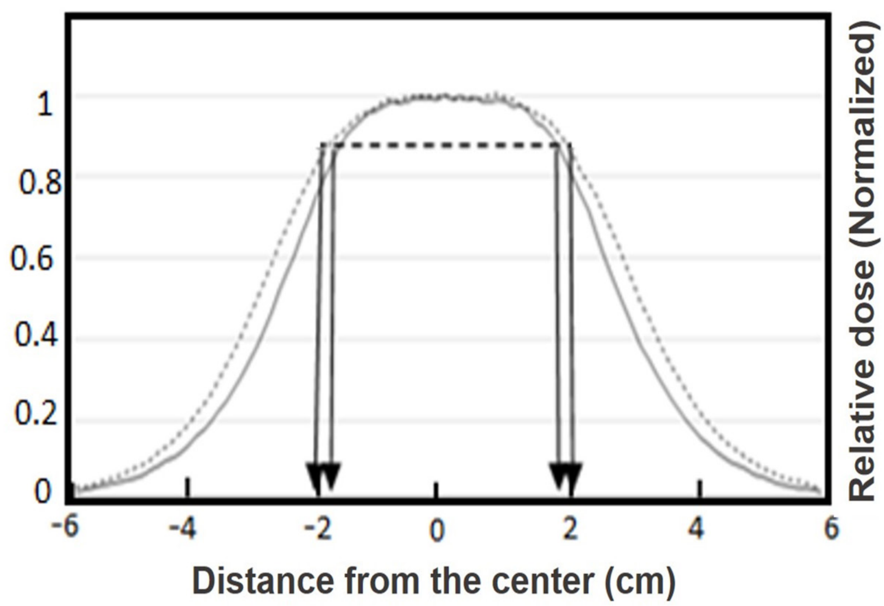

Figure 4: Flat beam profiles generated by contoured double scatterer (Solid line) and dual ring double scatterer (Dashed line)

tion of protons happened at the matters of dual ring scatterer versus double scattering system.

Discussion

In recent years, proton therapy facilities have been increasingly considered for tumor treatment due to physical properties of protons energy loss inside matter or patient body.

Several efforts have been working on different strategies of beam delivery step on tumor volume ranging from passive dose to active dose delivery or spot scanning method. The latter case is mostly in research step and most clinics or proton therapy centers are using passive dose delivery strategy.

In this method, the beam must be flattened at both lateral and longitudinal directions to cover the tumor volume as 3D uniformly. There are several methods for flat beam generation in lateral direction ranging from wobbler system in combination with single scatterer to double scattering system. It's worth mentioning that particles interaction with thin foils or layers differ from thick matters and multiple coulomb scattering rules must be taken into account here in the performance of double scattering systems.

Using wobbling system for flat beam generation has cost issue; moreover, enough space at target room is needed for installing vertical as horizontal magnets. Due to this, double scatterer systems are more interesting and feasible especially where the space is restricted at target room. In our last study, a simple double scatterer system was designed to make proper flattening according to lateral size of various tumors.

This work that is in continue of our previous study is a simulation investigation on the performance of dual ring double scatterer system as another strategy to be considered for implementation at CYRIC center, Tohoku University for generating flat beam profile. Thus, FLUKA simulation code was used to calculate the proper material and dimension of all required devices at dual ring double scatterer construction.

Final analyzed results show that dual ring scatterer is able to produce proper flat beam with reasonable treatment region to cover the tumors with each given lateral size (Figure 4).

It should be noted that the produced treatment region has reasonable uniformity according to the definition of uniformity degree formula [21-22]. Moreover, the semi-penumbra of flat beam profile representing the protons with non-uniform 3D spatial distribution is stopped with proper collimators and only the protons with uniform spatial distributions are allowed to pass and penetrate to the patient body and irradiate target volume. Apart from advantages of double scatterers, this system has some challenging issues. Firstly, since there are two scatterers in this strategy, energy loss of protons in not negligible due to the considerable total thickness of dual scattering systems. It also should be noted that the amount of energy loss is not constant for all crossed particles due to a) different thickness of second scatterer at double scattering system and b) different material and thickness of each ring mounted at dual ring double scatterer. In order to address this issue, energy compensator is coupled with second scatterer and shift the Bragg peak curve similarly for all proton particles.

As seen in Figure 3, there is a difference between Bragg peak curves (as 5 mm) by using two scattering systems. The amount of energy loss of protons at dual ring system is more than other systems since the total thickness of first and second scatterers at dual ring based method is more than the same value at contoured double scattering method. Moreover, since the number of protons interaction with matters inside dual ring is more than double scatterer, total number of produced neutrons is larger. This is due to the type of materials used in this system and dimension of scatterers. Since the produced neutrons may reach patient body, this drawback should be taken into account at treatment room. Future studies can include an assessment on the source of neutrons and gamma produced at treatment rooms and from patient body. Moreover, the amount of these neutrons and the strategies to minimize the presence of neutrons may be valuable for investigation. Moreover, assessment of beam flattening on Carbon and Oxygen ions as new therapeutic beams can be done using the same strategy. It should be noted that two scattering systems are sensitive in alignment with beam central direction in comparison with wobbler system, while any tilting may cause non-uniform results.

Conclusion

This study simulates the performance of a dual ring double scattering system by means of FLUKA code. The optimum dimensions and materials of scatterers used in this system can generate 40 mm flat treatment region using proton beam. The final results were compared with results obtained from contoured double scatterer in our last study and there was a close correlation between the performances of both systems. Moreover, the effect of secondary neutrons, produced due to protons interaction with these systems was investigated, quantitatively.

Authors' Contribution

The whole text of the article was written A. Esmaili Torshabi and the results and analysis were carried out by R. Ghasemkhani. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The achievements reported in this article are obtained from Monte Carlo FLUKA simulation code, confirmed by Graduate University of Advanced Technology, Kerman, Iran.

Conflict of Interest

None

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