Journal of Pharmaceutical Research International

30(6): 1-11, 2019; Article no.JPRI.52108
ISSN: 2456-9119
(Past name: British Journal of Pharmaceutical Research, Past ISSN: 2231-2919, NLM ID: 101631759)

An Iterating Method to Calculate the Geometry of Range Modulation Wheel in Passive Proton Therapy

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Authors' contributions

This work was carried out in collaboration among all authors. Author ZST designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors MS and MRG managed the analyses of the study. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JPRI/2019/v30i630283
Editor(s):
(1) Dr. Rafik Karaman, Professor, Department of Bioorganic Chemistry, College of Pharmacy, Al-Quds University, Jerusalem, Palestine.
Reviewers:
(1) A. Ayeshamariam, Khadir Mohideen College, India.
(2) Jackson Akpojaro, University of Africa, Toru-Orua, Nigeria.
Complete Peer review History: http://www.sdiarticle4.com/review-history/52108

Original Research Article

Received 15 August 2019
Accepted 20 October 2019
Published 25 October 2019

ABSTRACT

In the passive method of proton therapy, range modulation wheel is used to scatter the single energy proton beam. It rounds and scatters the single energy proton beam to the spectrum of particles that covers cancerous tissue by a change in penetration depth. Geant4 is a Monte Carlo simulation platform for studying particles behaviour in a matter. We simulated proton therapy nozzle with Geant4. Geometric properties of this nozzle have some effects on this beam absorption plot. Concerning the relation between penetration depth and proton particle energy, we have designed a range modulation wheel to have an approximately flat plot of absorption energy. An iterative algorithm programming helped us to calculate the weight and thickness of each sector of range modulation wheel. Flatness and practical range are calculated for resulting spread-out Bragg peak.

Keywords: Simulation; Monte Carlo; Geant4; proton therapy; range modulation wheel.

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1. INTRODUCTION

In cancer treatment, hadron therapy is a good method because of its minimum disturb on healthy cells, Comparing with other radio therapy methods [1]. Healthy cells Distribute can be dangerous for some tissues such as brain and liver. For children cancers this subject will be more sensitive. [2,3,4].

The proton beam that is used for tumour treatment, must have 160 to 230 MeV energy when coming out of the synchrotron, to penetrate in body tissue and transfer its energy to the cancerous target [5]. These particles lose most of their energy in a special depth of body. So single energy proton beam targeting only one point of tissue depends on its energy. Passive scattering is a method to cover all of the cancerous tumor volume. In this method, a single energy proton beam is reduced to a spectrum of different energy proton particles by scattering [6].

The most important scattering tool in a nozzle of proton therapy passive method is a rotating modulation wheel (RMW) to change energy and path of the particles to cover target bulk [7]. RMW with circular cross-section made of some sector of lead and Lexan with different angel and thickness.

Calculating the angle and thickness of each sector can be a complex process. Some analytical or simulating methods are used to obtain these geometrical data. In 2004 Gottschalk designed a software related to MCNP, called NEU to calculate geometrical properties of first and second scatter of passive scattering proton therapy nozzle [6]. Jia designed an RMW with simulation in Geant4 [8]. In this article, we have a calculation of each implement role and obtain geometric properties of a range modulation wheel to have a SOBP in absorption diagram.

2. MATERIALS AND METHODS

For calculating the absorbed dose, Monte Carlo method is a good approach. Geant4 is an open-source pack that is written in C++ object-oriented programming. Geant4 simulates all interactions that happens for particles inter a new Environment. Electromagnetic and nuclear interactions are simulated and calculated [8]. Physics List in the main file determines that which interactions happen for a particle and how it behaves. Physics list, QGSP_BIC_EMY is the most suitable physics list for proton collisions and results in more accurate data [9].

In spite of the example of Hadron therapy, we used Run & Event example. Then we changed material and geometrical properties in Detector Construction files and type and number of particles in macro files.

2.1 The Simplest State

A cubic phantom of water in 40×40×40 cm dimensions was considered and a 10×10×40 cm detector in center to detect absorbed dose. A point source of proton on the left of the phantom sends it 100,000 particles. Depth-absorbed dose plot should be in the form of the Bragg peak and penetration depth for different energies must be according to reliable sources.

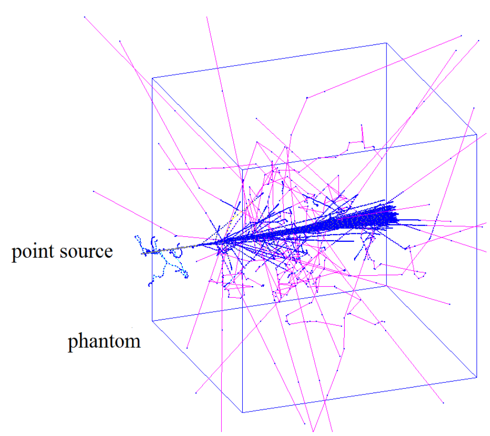

Fig. 1. The phantom of water to 40 cm side and a point source of proton

Table 1. Geometrical properties of some tube shapes

	shape	Inner radius (cm)	Outer radius (cm)	Length (cm)	Location (cm)	material
Shielding	tube	20	25	250	(0,0,-45)	Brass
S1(RMW)	complex	2	8	variable	(5,0,-290)	Lead&Lexan
S2	complex	0	6.5	variable	(0,0,-240)	Lead&Lexan
Collimator1	tube	6.5	10	4 cm	(0,0,-240)	Brass
Collimator2	tube	12.5	20	20	(0,0,-190)	Brass
Collimator3	tube	12.5	20	20	(0,0,-120)	Brass
Collimator4	tube	12.5	20	20	(0,0,-75)	Brass
Aperture	tube	10	20	20	(0,0,-55)	Brass
patient compensator	Tube-half sphere	0	18	10	(0,0,-150)	ABS resin

2.2 The Effect of Lexan or Lead Slab on the Proton Beam Path

In the second state, a Lead or Lexan slab put at a distance of 10 cm from the proton source Variation in slab's thickness, leads to changing absorption plot.

If we assign specific weight to each Bragg peak and add them together, we can achieve a flattened absorbed dose curve within the tumor. This curve called Spread Out Bragg Peak (SOBP). Several Bragg peaks with special weights lead to a SOBP plot.

A slab with determined thickness decreases energy of particles crossing it. The amount of energy reduction is related to the slab's thickness and material.

2.3 Geant4 Run with Proton Therapy's Nozzle

A point source of proton that radiates one million particles, is located in 3 meters before cubic phantom of state 1. A proton therapy nozzle that Guan is mentioned in his PhD thesis [10] is set in this distance. It's included of a cylinder shielding, two scatterers, four collimators, an aperture and compensator are on the proton path. Nozzle output inter a cubic phantom of water. Cylindrical shielding made of brass (Cu & Zn) covers some other implements. Material properties are in 'Nist Manager' List. For new material definition, we need to know weight percent or number of each element in material combination. Each element contribution in Lexan, Brass and ABS resin are in Table 2.

Four collimators, one around second scatterer and three collimators are situated in 50 cm apart [11]. Fig. 2 is the nozzle in our Geant4 simulation. A cylindrical aperture and specific patient compensator are at the end of the nozzle. Geometrical properties are in Table 1.

The first scattering device RMW, called S1 with some sectors is seen in Fig. 3. Each sector contains layers of Lead and Lexan with different thicknesses to scatter particles, decrease protons energy and alienate them from their path.

To produce SOBP, the single energy beam of proton, passes a Rotating S1. Each sector of RMW decreases energy of proton beam crossing

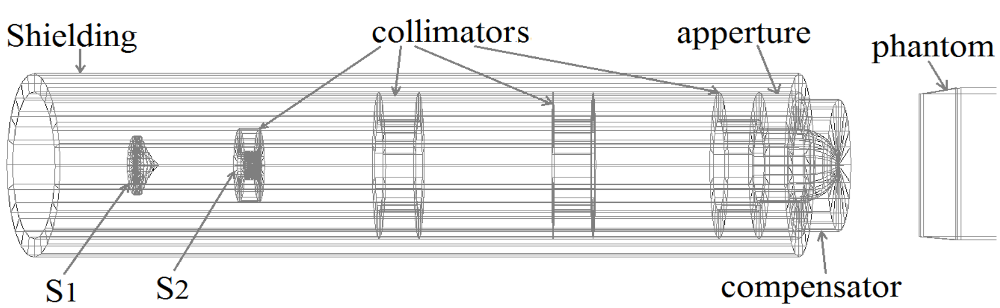

Fig. 2. A general picture of a nozzle

Table 2. Weight percent or number of atoms in new materials

Material	Weight percent or number of atoms		
Lexan	Hydrogen 5.5%	Carbon 75.6%	Oxygen 18.9%
brass	copper 67%	zinc 33%	
ABS Resin	hydrogen 64atoms	carbon 58 atoms	Nitrogen 2 atoms

it. The angle of each sector determines the weight of that Bragg peak. If we show total absorbed dose with D_{total}, the angle with A (degrees) and weight with W, we have:

$$D_{total} = \sum_i W_i D_i$$

$$W_i = \frac{A_i}{360^{\circ}}$$

Some implements made of heavy and light atoms scatter the proton beam. Heavy atoms such as Lead scatters protons in bigger scattering angle, but light atoms such as hydrogen, carbon and oxygen decree particles energy in smaller scattering angle [6,7]. So lead is used for traditional scattering and Lexan is used to do this duty longitudinally.

The Second scattering tool also contains these two layers but is different geometrically. Fig. 4 shows geometry of the second scatterer that first collimator is located around it. The role of second scatterer, collimators, aperture and compensator avoiding particles from radiating surrounding the nozzle and tumor [10].

The geometrical data of S1 and S2 obtained from NEU in Tables 3 & 4 are used in this state.

According to Table 1, S1 center is located in (5, 0, -290) cm. It means that the center of S1 displaced to a width of 5 cm to pass through the beam of protons. To achieve SOBP, S1 rotates a round and in each 0.25 degree a run executes. Whiles a sector stands on proton beam path and scatters it related to its diameter [8]. Superposing absorption plots lead to a new plot that we expect to be flat maximum in tumors position. In each run, 1500 particles are radiated toward phantom. Finally absorbed energy of more than 2 million particles in 1440 case summed with each other. Geometry of Range modulation wheel is important to get dose desired pattern.

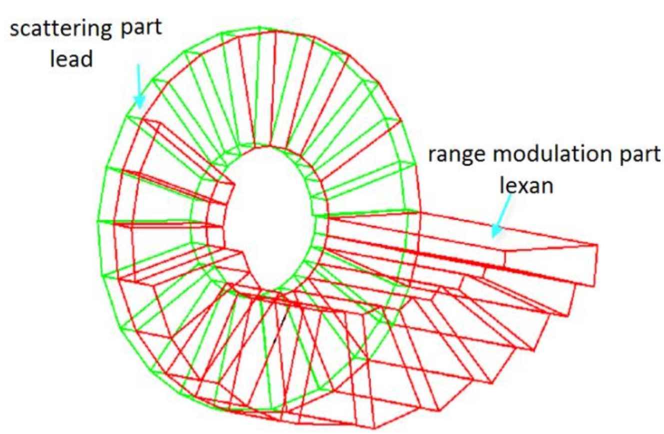

Fig. 3. Range modulation wheel (RMW) to produce SOBP

Table 3. Parameters of S1 from NEU in Guan thesis

Sector number	sector weight	Lead thickness(cm)	Lexan thickness(cm)
1	0.4603	0.6451	0.0001
2	0.1571	0.6316	0.9198
3	0. 1106	0.6168	1.8464
4	0.0843	0.6012	2.7768
5	0.0705	0.5850	3.7106
6	0.0554	0.5681	4.6475
7	0.0618	0.5507	5.5877

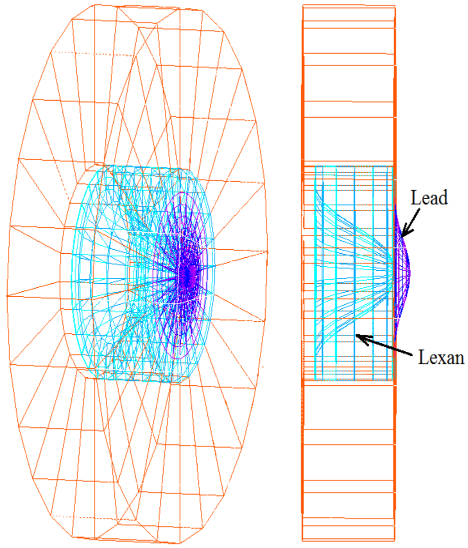

Fig. 4. The second scatterer

Table 4. Parameters of S2 from NEU in Guan thesis

Ring number	Ring radius(cm)	Lexan thickness(cm)	Lead thickness(cm)
1	0.0000	0.0999	0.6656
2	0.4442	0.3338	0.6194
3	0.8885	0.9420	0.4990
4	1.33327	1.7482	0.3394
5	1.7769	1.5463	0.1812
6	2.2212	3.1254	0.0664
7	2.6654	3.4338	0.0052
8	3.1096	3.4600	0.0000
9	3.5539	3.4600	0.0000
10	3.9981	3.4600	0.0000

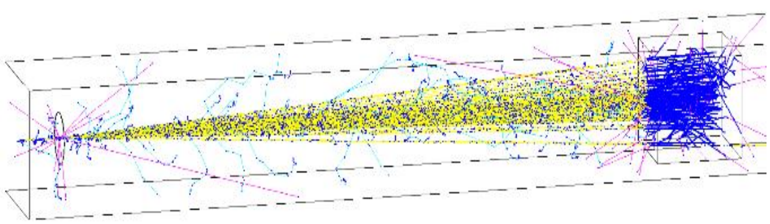

Fig. 5. Scattering from lead disc 0.2 cm thickness

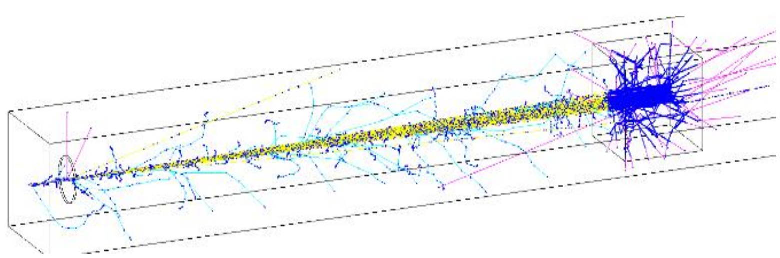

Fig. 6. Scattering from lexan 1 cm thickness

2.4 Calculating a New S1 with Programming

Because we cannot use NEU for calculating angles and thicknesses of several sectors of RMW. Sector angle is determined with weight quantity. Table 3 shows this data obtained from the iterative program. For producing input data we must use a disk made of lead or Lexan in RMW place. But scattering angle in lead scattering is big. So a lot of particles lost. Absorbed dose in phantom for Lexan disks with different thickness 0, 1, 2, …, 7 cm can help us. For each plot a weight number is necessary. For a 6 cm diameter tumor, it must be checked if traditional scattering covers all tumours diameter. If 2.5 cm Lexan disk is not sufficient it is necessary to use a thin lead disk.

With an iterative algorithm program each sectors weight was obtained, in Table 4. This numbers determine sectors angles. For evaluating flatness of resulting SOBP, we can use the following formula. That D and $D_{mean}$are related absorbed dose and mean value of it in tumor region [12].

$$F = \frac{(|D - D_{mean}|)_{max}}{D_{mean}} \cdot 100$$

If we take D_{mean} dose 100%, M_{95} is distance between two 95% points in two proximal and distal regionns and practical range is distance between two 90% point of D_{mean}. In distal penumbra 90-10% and 80-20% penumbras on depth axe are two parameters that are evaluated in SOBP plot.

3. RESULTS AND DISCUSSION

In simplest condition we have a point source and a phantom. 100,000 proton particles with single energy eradiated to cubic phantom of water with 40×40×40 cm^3 dimensions. Fig. 4 shows deposited energy in this phantom for eight energies 100, 120, …, 230 MeV. Eight Bragg peaks that determine penetration depths for each beam of energy, are compatible with experimental reports [13,14,15].

Executing run using geometry data from Tables 3 and 4, obtained NEU and summing 1440 data file, results in relative dose plot of Fig. 8. This plot contains two curves that gained in presence of RMW on proton beam path upstream. The higher plot illustrates relative dose in S2 presence and the shorter, displays relative dose in the absence of S2. The effect of S2 is visible in this graph.

For calculating sectors angle, it's helpful to survey effect of a lead or Lexan disc with different thickness on 230 MeV proton beam Bragg peak. Figs. 9a and 9b show deposited energy in two different detectors in presence of lead disc with thickness of 2 mm, 4 mm, …, 20 mm.

Difference between heights of two plots indicates that lead disk scatters proton beam with big angles. So lots of particles lose.

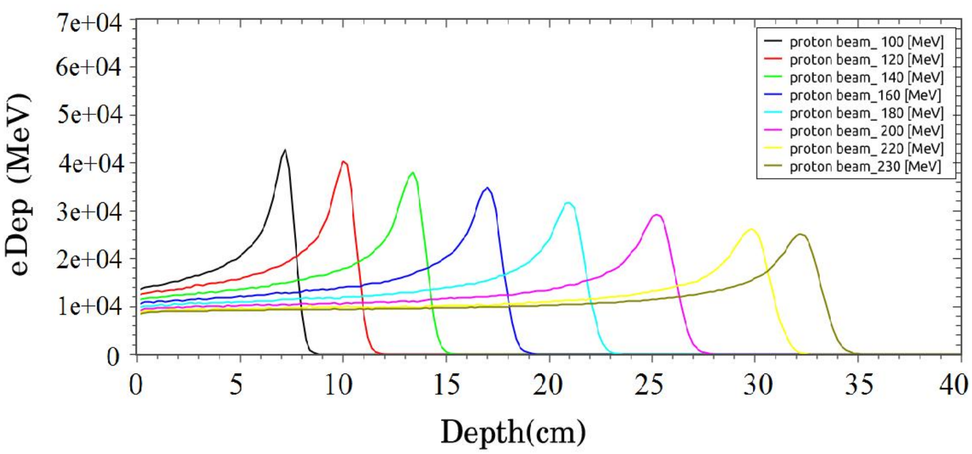

Fig. 7. Deposited energy in cubic phantom. Each plot is related to 100,000 single energy proton particles with 230, 220, 200, 180, 160, 140, 120, 100 MeV energy

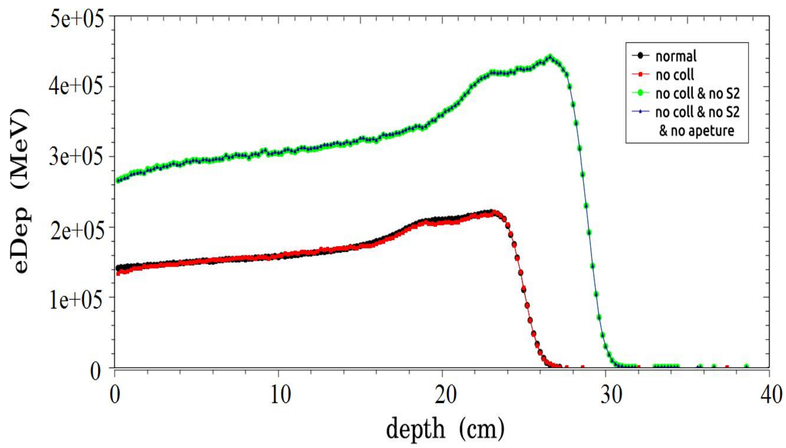

Fig. 8. The effect of second scatterer on SOBP figure

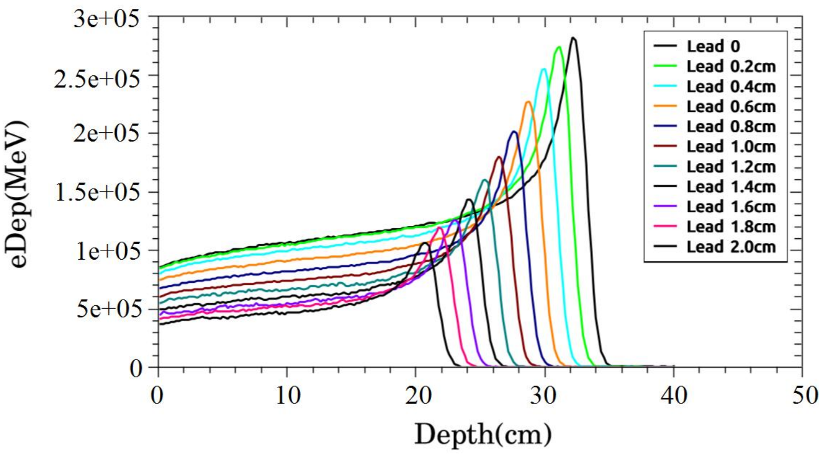

Fig. 9a. Absorbed energy in 40×40×40 cm3 detector. The highest peak is Principal Bragg peak from 100,000 proton particle with 230MeV energy. Putting a Lead disc with 2 mm, 4 mm, …, 20 mm thickness leading to other peaks with less penetration depths

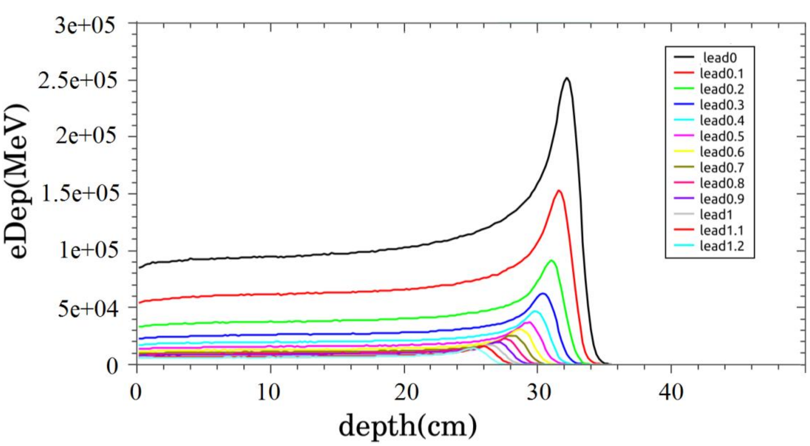

Fig. 9b. Absorbed energy in 10×10×40 cm3 detector. The highest peak is Principal Bragg peak from 100,000 proton particle with 230MeV energy. Putting a Lead disc with 2 mm, 4 mm, …, 20 mm thickness leading to other peaks with less penetration depths

Comparing Figs. 10a and 9a shows that the ability of Lead disc with defined thickness is equal to Lexan disc ability with 5 times thickness to decrees proton beam energy. But Lead scatters particles with bigger scattering angle. So more particle go away and peak heights in Fig. 10b is less than Fig. 10a.

It is visible in Figs. 5 and 6 that Lexan disk scatters proton beam in smaller angles. So for producing SOBP plot it is better to use Lexan sectors because of losing less particles. The angle of each sector determines with weights got from output program.

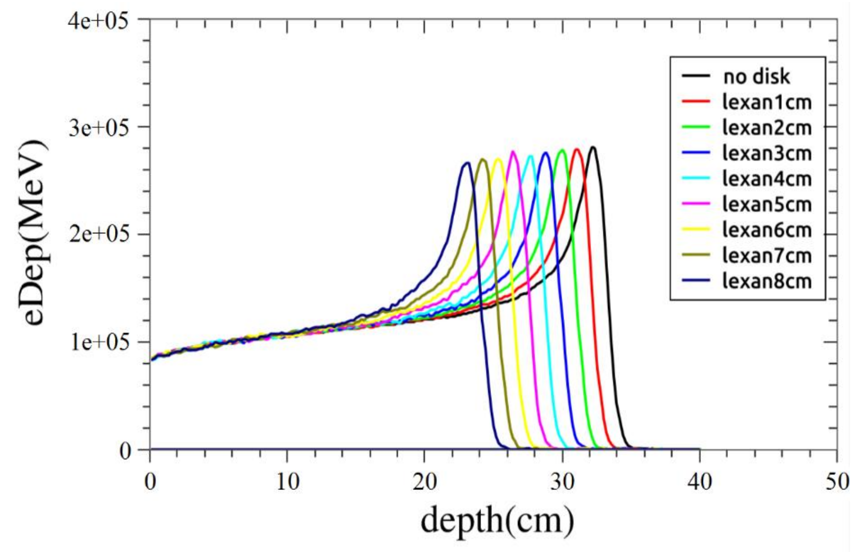

Fig. 10a. Absorbed energy in 40×40×40 cm3 detector. The highest peak is Principal Bragg peak for 230MeV proton beam. Putting a Lexan disc with 1 cm thickness leading to second peak with less penetration depth

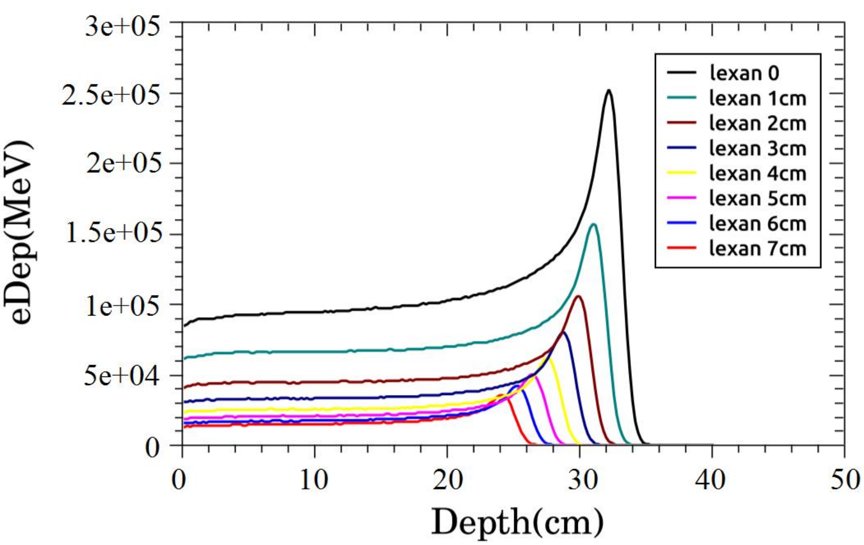

Fig.10b. Absorbed energy *in* 10×10×40 cm3 detector. The highest peak is Principal Bragg peak for 230MeV proton beam. Putting a Lexan disc with 1 cm thickness leading to second peak with less penetration depth

Table 5. Parameters of S1 from iteration method

Sector number	Sector weight	Sector angle (deg)	Lexan thickness(cm)
1	0.495843	178.50	2
2	0.094274	33.94	3
3	0.074158	26.70	3.5
4	0.014675	5.28	4
5	0.143483	51.65	4.5
6	0.0887836	31.96	6
7	0.0887836	31.96	6.5

Using the previous step information and iterative program, we obtained weights and thicknesses for a simple RMW. In Table 5, we see two column of thickness and weights of sectors. Each thickness weight of lexan obtained from itterative program for producing SOBP in depth of 24 cm to 30 cm of water phantum. Fig. 11 is outcome SOBP of Table 5.

Practical range, M_{95}, 90-10% Penumbra, 80-20%Penumbra and flatness of resulting SOBP are shown in above Table 6.

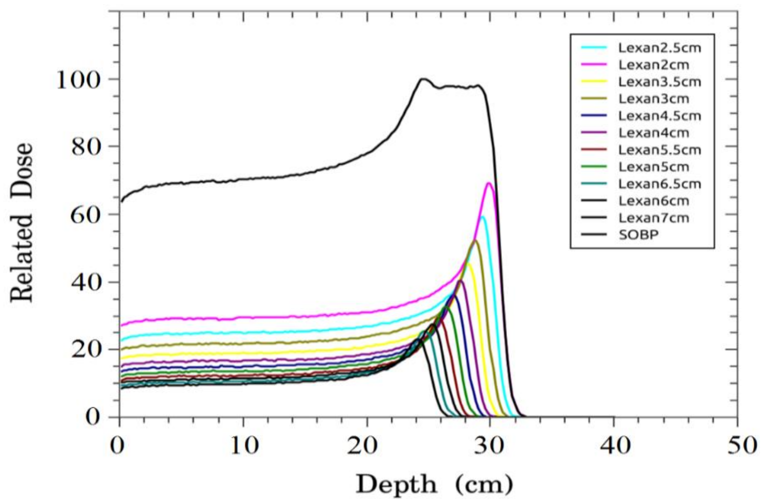

Fig. 11. SOBP obtained iterating program

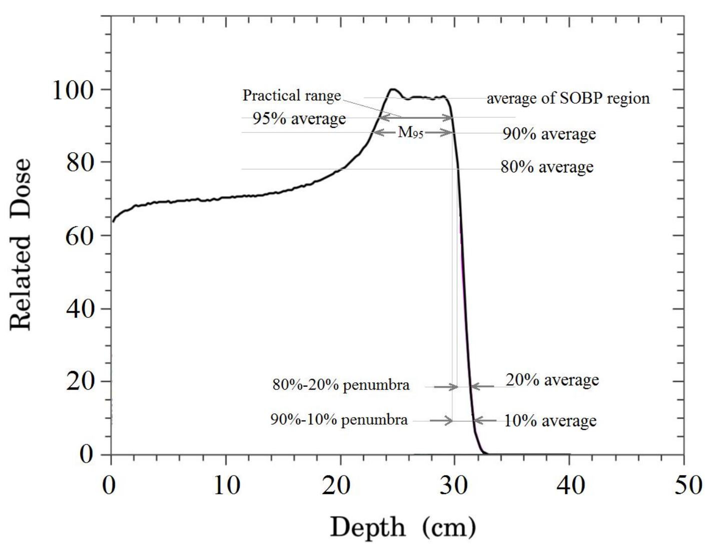

Fig. 12. Flatness, practical range, M_{95} of SOBP

Table 6. SOBP plot properties

Practical range (mm)	M_{95} (mm)	90-10% Penumbra (mm)	80-20%Penumbra (mm)	Flatness (%)
72.3	63.6	16.8	11.4	3

4. CONCLUSION

Brass shielding and collimators doesn't have any effect on absorbed dose. They are necessary for stopping particles radiates surrounding the nozzle and detector. RMW is important to produce a SOBP for absorbed dose. With an iterating program we can obtain angle and thickness of sectors to produce SOBP. A good flatness of 3% is acceptable for SOBP region with this accuracy.

By raising the accuracy in thickness, we can achieve a smoother SOBP. With an iterating program it's possible to have a simple design RMW. But to have more flatness it is better to calculate deposited energy curve for more thickness disks of Lexan with more accuracy.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/52108