

Optimization of Energy for Proton Therapy with Pencil Beam Collimator Model in Craniopharyngioma Tumor Using MCNP6 Code

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ABSTRACT

Computational simulations of proton therapy with a pencil beam collimator for craniopharyngioma have been done using MCNP6. A pencil beam was radiated towards cube shaped tumor cells in size 1.2 cm, located at a 5.4 cm depth from the surface of the scalp. A 0.1 cm pencil beam was radiated from the left 19.6 cm from the scalp. The cube of tumor cell is divided into the front layer, middle layer, and back layer. Each layer of the tumor cell is divided into 9 cubicles, thus there are 27 cubicles. Using various energy from 108 MeV to 115 MeV and various intensity of energy for each irradiation, it produces the dose for each cubicle in unit MeV/gram per proton. The best isodoses occurred in 5 variations of energy which is 108.2; 111.2; 113.4; 114.7 and 115 MeV. The healthy organ that received the largest dose of the proton is the brain, it is $(7.38 \pm 0.01) \times 10^{-2}$ MeV/gram per proton, or only 0.412% compared to the tumor cell dose.

1. Introduction

Craniopharyngioma is a benign tumor that arises due to underdeveloped squamous epithelial tissue of Rathke's pouch. Craniopharyngiomas are rare in cases of intracranial tumors, only about 7.8% in pediatric tumors and (1-4)% in adult tumors. These tumors usually attack children at the age of (5-14) years and adults at the age of (50-70) years [1]. These tumors are located in the parasella region adjacent to the frontal lobe, temporal lobe, cranial fossa and brain stem. Judging from its proximity to important parts of the brain, the spread of this tumor is quite worrying. Craniopharyngiomas are usually found in children aged 5-14 years and adults over 50 years of age [2].

Among all the craniopharyngioma treatments that have been suggested, there is another option, namely proton therapy which is can make the radiation focus on the tumor cells and slightly affect the surrounding healthy cells. Proton therapy has a clear theoretical dosimetric advantage with a peak Bragg dose distribution (Bragg Peak or BP) compared to conventional radiotherapy using photons [3]. The dose absorbed by the body increases as protons slow down at greater depths until the absorbed dose rises to a sudden peak called the Bragg peak. The proton beam can be programmed so that the Bragg peak occurs right within the tumor site. After the peak of Bragg, there is a steep dose reduction, which eliminates unnecessary doses [4]. A comparison of the dose distribution of conventional X-ray radiotherapy and proton therapy can be seen in Fig. 1. In X-ray radiotherapy, radiation dose is distributed very

high at baseline and decreases with increasing depth, whereas in proton therapy, the proton dose is distributed only at a certain depth [5].

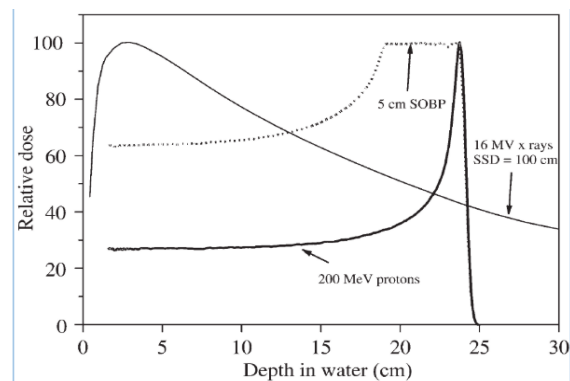


Fig 1. X-ray dose comparison with the proton Bragg peak [6]

The use of Pencil Beam Scanning (PBS) in proton therapy can help direct the radiation to a specific point. The proton beam will narrow and focus on the intended point only. The use of this pencil beam can reduce hardware for one session therapy, also can make the therapy time much shorter. The dose distribution value in the pencil beam is very effective for dealing with large and thick targets that are very difficult to irradiate with a uniform proton beam. Information about the traces of protons in the body is indispensable. The proton beam in the form of a pencil beam should be sought so that the radiation target to tumor cells is precisely targeted with the least negative effect on nearby healthy cells. Pencil beam has a maximum size of 10 mm [7].

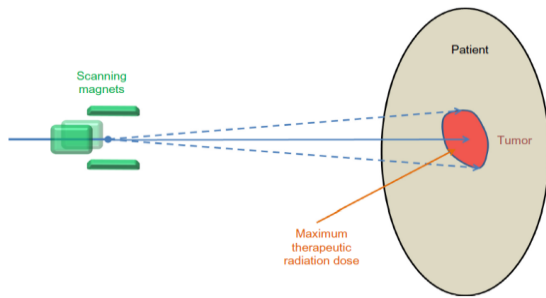


Fig 2. Illustration of pencil beam scanning on proton therapy [9]

In PBS, radiation dose distributing within the patient is controlled by the scanning magnet, not beam-forming hardware such as scatters or collimators. In PBS, the initially accelerated beam will reach the desired energy. Then this small beam (called a "pencil beam") passes through two sets of orthogonal magnets. Magnetic strength of the two sets of magnets can be adjusted, thus the pencil beam can be shifted in the selected direction. One of the important advantages of PBS is that it is possible to adjust the intensity of the proton beam used [8].

Ideally, the beam is in the form of PBS so that the dose of protons received by tumor cells can be evenly distributed and slightly hit healthy cells around the tumor cells, this uniform dose is known as isodose. Research conducted by Bolsi, et al (2020) demonstrated the modeling of proton therapy in craniopharyngiomas using software based on the Monte Carlo method, namely Geant4 [9]. To achieve isodose, a proton beam measuring 0.2 cm is used which has 27 energies in the range of 100 to 226.7 MeV. This study shows that the dose received by cancer cells still has not reached isodose and healthy cells around cancer cells receive very few doses of protons which are declared safe by the OAR.

There is a modeling software using the Monte Carlo method, namely MCNP6. *Software* MCNP6 for modeling consists of three main parts, namely cell cards, surface cards, and data cards [10]. It was developed by the National Laboratory of Los Alamos. MCNP6 is a development of the previous versions of MCNP, namely MCNPX and MCNP5. A total of 37 types of particles can be traced, including elementary particles, composite and antiparticle particles, and nuclei. Proton physics interactions are represented as elastic and inelastic nuclear scattering, continuous slowing down approximation (csda), scattering energy and angle, and magnetic field effects. However, a newer and recently improved model used by MCNP6 is the Cascade-Exciton Model (CEM) nuclear reaction [11].

Cancer therapy modeling with MCNP-based simulation has been developed at the Physics Study Program, FMIPA UNS. Khoirunnisa (2021) demonstrated the modeling of proton therapy in nasopharyngeal carcinoma using MCNP6 software. In this study, cancer cells were simulated to be round in shape with a diameter of 1.56 cm. The irradiation was carried out from the right and left with a proton beam of 0.41 cm in diameter. The

proton energy used starts from 103 MeV to 109 MeV. The large diameter beam causes the beam inaccurate radiate on cancer cells so that, from this study the cancer cells was not reached isodose. Khoirunnisa (2020) proposes to use smaller beam size. Husna (2022) conducted a research on proton therapy modeling in lung cancer using the pencil beam feature with MCNP6. Husna (2022), modeled a cancer cell in the form of a block consisting 9 small cubicles and used 9 proton sources that located parallel to each cubicles. The proton energies that used for this research are 94 MeV and 104 MeV. And got the result that the two proton energies are not optimal, so it is necessary to increase the amount of proton energy.

According to Winterhalter, et al (2020) energy from 108 to 115 MeV is energy that can reach a depth of 5.4 to 6.6 cm in the brain [12]. In addition to regulating energy, it is necessary to adjust the energy intensity accordingly. The intensity of this proton energy is related to the number of protons contained in each energy. The greater the energy intensity of a proton, the more protons are contained in the proton beam. This intensity adjustment is very important to achieve isodose because it can affect the amount of dose received by tumor cells. So the purpose of this research is shows the optimal proton beam energy in proton therapy for craniopharyngioma tumors treated using a pencil beam and Shows measurement of proton dose obtained by healthy cells around craniopharyngioma tumor cells.

2. Methods

Simulations to calculate the dose of proton therapy were performed using a phantom made by Lazarine (2006). In this study, only the head and neck phantom which has been added with tumor cell geometry is used. The geometry of the added tumor cells is modeled in the form of a 3×3×3 cube with a side length of 1.2 cm. The cube consists of 27 small cubicles modeled on being at the base of the brain close to the spine. The tally used is F5 because it is used for measuring dose. And used NPS or number of repetition in number 224.000.

In this simulation, the proton beam radiation source is placed parallel to the center of the cube as far as 19.6 cm from the body surface. Radiation is carried out from the left side of the head with the consideration that if from another direction the proton beam will hit other healthy organs such as the facial skeleton, eyes, sense of smell organs, cerebellum and spine. This is not in accordance with the ALARA principle. In this study, a proton source with a diameter of 0.1 cm was used.

3.1. Model Description

Fig. 3. shows the phantom geometry that we used in this simulation.

Information:

1. Head skull
2. Brain
3. Skeleton face
4. Craniopharyngioma tumor cell
5. Spine
6. Soft tissue of head and neck

- 7. Scalp and neck skin
- 8. Environment outside the body

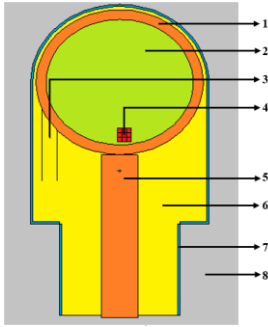


Fig 3. Phantom geometry of the head and neck in coronal section

In Fig 4. tumor cells are modeled in the form of a cube consisting of 3 main layers, namely the A layer or the front layer of the cube closest to the proton source, then the B layer or the cube layer in the middle of the cube, and finally the C layer or the back layer of the cube that is farthest from the proton source. In this study, all of the three layers must obtain the same dose. The proton beam is directed towards the center of the cube.

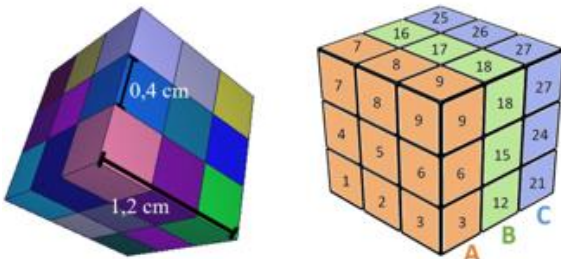


Fig 4. Geometry of craniopharyngioma tumor cell with cubicle numbers

Fig. 5 is an illustration for layer A irradiation is given.

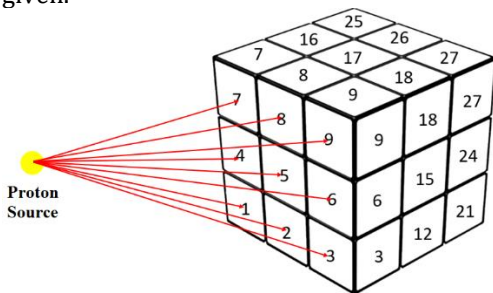


Fig 5. Irradiation illustration on the layer A

3. Results and Discussion

3.1. Absorbed Dose with 3 Variation of Proton Energies

Three variation of proton energy which is 108, 111.2, and 114.2 MeV has reached the back layer of the tumor cells, however the energy is not evenly distributed. The dose distribution for the three proton energies can be seen separately in Fig. 6. It shows the energy of 108 MeV gave the highest dose to layer A. The energy of 111.2 MeV gave the highest dose to layer B, plus a small dose of energy of 114.2 MeV. Meanwhile, for layer C, the maximum dose is given from 114.2 MeV of energy.

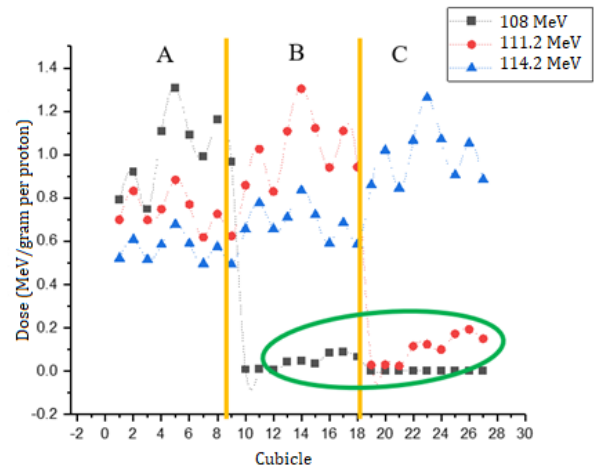


Fig 6. Dose distribution separately for 3 proton energies

Seen in green circles, for energies of 108 and 111.2 MeV the dose received by the cubicle increased even though the dose in the previous cubicle had reached 0. This is not in accordance with the Bragg peak, where after the dose reaches 0 it is impossible to increase the dose in the deeper position. This inconsistent result is due to the fact that the value of these fluctuations is a characteristic of the modeling.

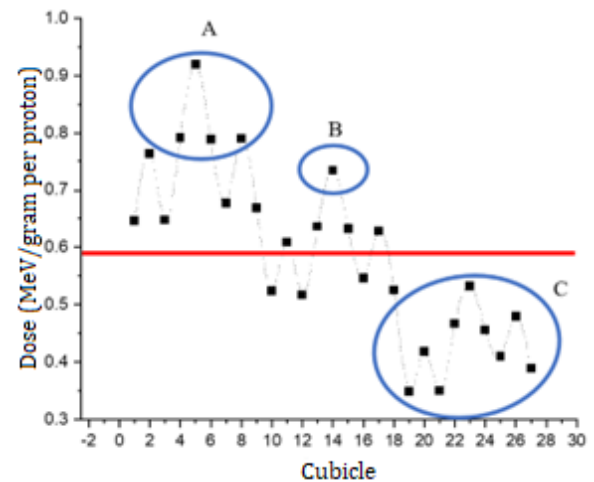


Fig 7. Dose received in each cubicle for irradiation with 3 proton energies

In Fig. 7, the scattered dose decreases in the deeper layer or farther from the proton source. It is also seen that the dose received by each cubicle fluctuates with the average dose or ideal isodose at (0.59 ± 0.15) MeV/gram per proton which is marked with a red horizontal line. In circle A, cubicles 2, 4, 5, 6 and 8 which are in layer A receive a sufficiently high dose away from the ideal isodose. It is also necessary to reduce energy intensity at 111.2 MeV because as shown in circle B, the dose for cubicle 14 is high and above ideal isodose. While in circle C, the dose given by the energy of 114.2 MeV with an intensity of 0.4 is still relatively low and far from the ideal isodose. Overall, irradiation with these 3 energies had an isodose rate of 74.47%.

3.2. Absorbed Dose with 4 Variation of Proton Energies

Radiation with 3 variations of proton energy showed a low level of isodose because the proton energy did not reach the entire back of the cubicle. To increase the isodose level, 113.4 MeV of energy was added and the energy changed from 114.2 MeV to 114.7 MeV. In Fig. 8 looks the same as the previous energy variation, where the energy of 108 MeV gives the highest dose to layer A. Meanwhile, layer B receives the most dose of energy 111.2 MeV and gets an additional dose of 113.4 and 114.7 MeV energies. And the additional energy of 113.4 MeV gives a dose that is almost the same as the energy of 114.7 MeV for layer C.

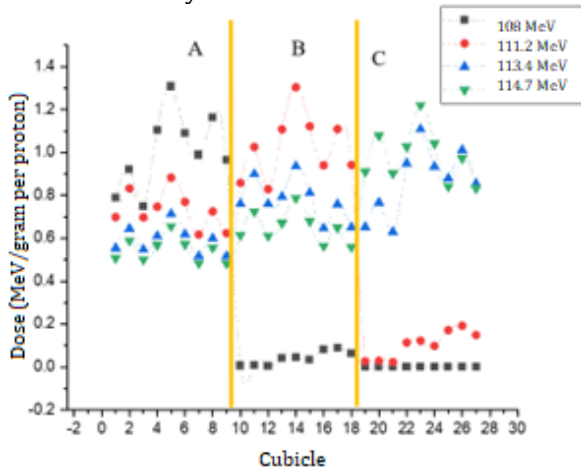


Fig 8. Dose distribution separately for 4 proton energies

The comparison of the dose distribution for irradiating 3 variations with 4 variations of proton energy can be seen in Fig. 9.

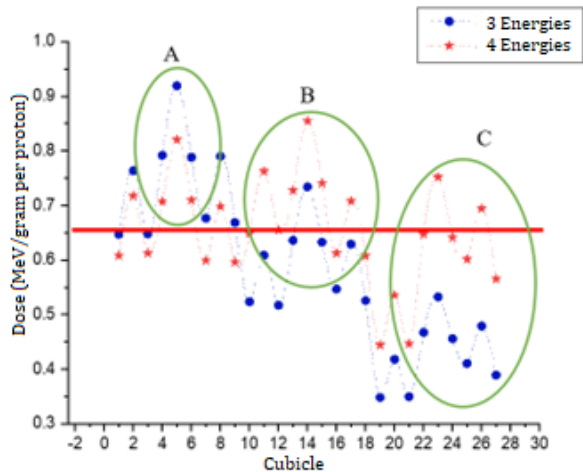


Fig 9. Comparison of dose distribution of 3 and 4 variations of energy proton

Unlike the previous irradiation, this 4 energies irradiation has average dose in a number (0.656 ± 0.097) MeV/gram per proton. This value is marked with a red line which is also considered as the ideal isodose. The isodose rate on this irradiation had a significant increase to 85.22%. From Fig. 9 in circle A, the dose received by cubicles 2, 4, 5, 6 and 8 in layer A decreased and approached the ideal isodose. Meanwhile, in circles B cubicles 12 and 16, the dose increased to close to the ideal dose. However, the dose received by cubicle 14 also experienced a

significant increase, thus avoiding the ideal isodose. Then it can be seen in circle C that the overall dose in layer C has increased very significantly so that each dose received by the cubicle can approach the ideal isodose.

3.3. Absorbed dose with 4 variation of proton energies

The variation of the 4 proton energies shows the isodose level that can still be increased because the proton energies of 113.4 and 114.7 MeV proved unable to reach the back cubicle evenly. As a result, added energy of 115 MeV which able to reach the rear cubicle. In addition, the energy of 108 MeV is considered still insufficient to give a dose for several cubicles at the bottom of A layer. Because of that it needs another proton energy which is 108.2 MeV.

To keep the A layer close to the ideal isodose, the energy of 108.2 MeV is set to a constant intensity of 0.1. Previously, the dose in layer B had not yet reached the ideal isodose, so that in this irradiation the energy intensity of 111.2 MeV was reduced to 0.25 and the energy intensity of 113.4 MeV was changed to 0.35. In order for the dose of cubicles 19 and 21 to be close to isodose, the energy intensity of 115 MeV is set to 0.2. Comparison of radiation dose distribution of 3 variations of energy with 4 variations of energy can be seen in Fig. 10.

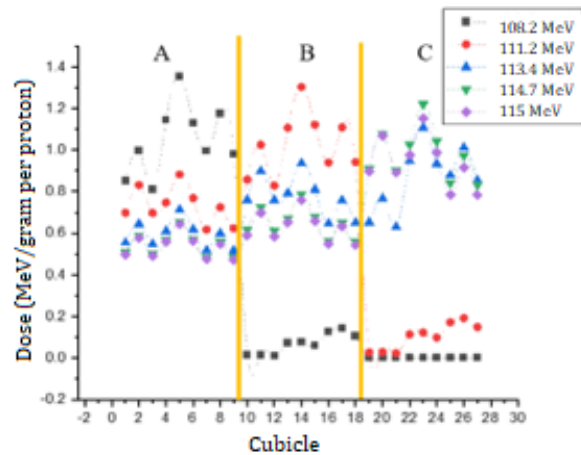


Fig 10. Dose distribution separately for 5 proton energies

Comparison of radiation dose distribution of 4 variations of energy with 5 variations of energy can be seen in Fig. 11.

This irradiation has an ideal isodose value of (0.664 ± 0.091) MeV/gram per proton and has a higher isodose level than the previous irradiation of 86.35%. This can be seen from Fig. 11 where more cubicles received doses close to the ideal isodose than the previous irradiation. From Fig. 11, it can be seen in circle A, the energy change from 108 MeV to 108.2 MeV resulted in the dose received by cubicles 4, 5, 6, and 7 which were in the lower layer A reduced to the ideal isodose. However, in circle B, cubicles 12, 13, 14, and 15 which are in the middle layer B have increased doses so that they are away from the ideal dose. Finally, at circle C, an additional 115 MeV of energy impacts cubicle 19.

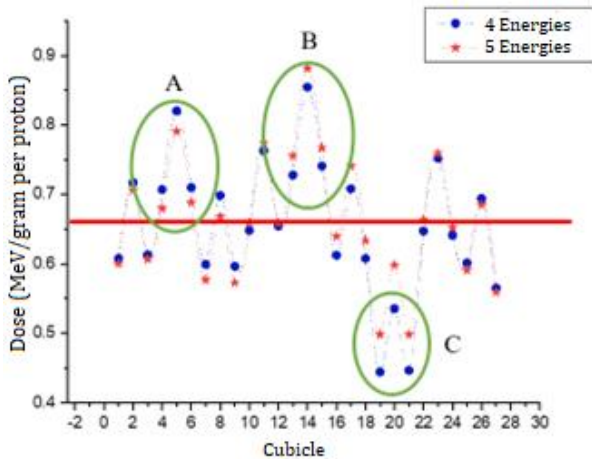


Fig 11. Comparison of dose distribution of 4 and 5 variations of energy proton

The difference in isodose levels for 4 and 5 energy variations is 1.13%. This difference is considered not too significant, because of that this study does not add any more energy variations and irradiation with 5 energies is considered the best irradiation. Besides, according to Hashemi et al (2020) the isodose level for irradiation with 5 variations can be said to be the optimal energy variation [13].

3.4. Dose Received by Healthy Organs

In any radiation therapy, healthy cells around the tumor cells will receive radiation as well. In proton therapy healthy cells through which protons pass will still receive the dose but very little. This is because of the characteristic of the proton that it has a Bragg peak where the proton will only ionize at a certain depth. In this simulation, it seen that a healthy cell is passed by a proton beam. These healthy cells can be seen in Fig. 12.

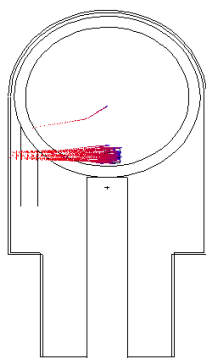


Fig 12. Visualization of a proton beam from the left hitting a healthy organ around craniopharyngioma tumor cells

It can be seen in Fig. 12 that healthy organs that receive a dose of proton beam are the scalp, facial skeleton, skull bone, soft tissue in the head and brain where the craniopharyngioma tumor is located. It means that there are protons that bend into the upper brain, meaning that it is possible that the proton beam also hits other organs that it does not pass. Although it is far away, it is possible that the proton rays also hit the spine. Although the

healthy organs are receive dose of protons as well, this dose is not harmful to healthy organs. Because the percentage of the dose received by healthy organs is very small compared to tumor cells which are the main targets of this simulation.

4. Conclusions

Based on the proton therapy simulation research that has been carried out, the following conclusions were obtained. First, the most optimal proton energy for the treatment of craniopharyngioma tumors is with 5 variations of proton energy, namely 108.2; 111.2; 113.4; 114.7 and 115 MeV resulted in a proton therapy dose of (17.901 ± 0.01) MeV/gram per proton with an isodose rate of 86.35%. And the second is the healthy organ that received the largest proton dose was the brain organ with a dose value of $(7.38 \pm 0.10) \times 10^{-2}$ MeV/gram per proton or 0.412% compared to tumor cell dose.

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