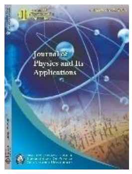
Journal of Physics and Its Applications

Journal homepage : https://ejournal2.undip.ac.id/index.php/jpa/index



Dose Distribution of Pencil Beam Proton Therapy using Geant4 Simulation for Breast Cancer Treatment

Rizki Budiman[1], Heri Sutanto[2], Rasito Tursinah[3], Pandji Triadyaksa[2*]

[1]*Magister of Physics, Department of Physics, Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia*
[2]*Department of Physics, Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia*
[3]*Research Organization for Nuclear Energy, BRIN, Tangerang, Indonesia*

[*]*Corresponding author: p.triadyaksa@fisika.fsm.undip.ac.id*

ARTICLE INFO

Article history:
Received: 18 November 2024
Accepted: 12 May 2025
Available online: 31 May 2025

Keywords:
Breast Cancer
Dose Distribution
Pencil Beam
Proton Therapy
Spread-Out Bragg Peak (SOBP)

ABSTRACT

This study aims to obtain a Spread-Out Bragg Peak (SOBP) for breast cancer treatment using proton pencil beams Monte Carlo simulation. Proton beams with 2 MeV energy steps from 70 to 110 MeV were simulated using Geant 4 software to generate the SOBP. The optimization tool Linear Least Squares (lsqlin) was used to configure the proper proton beam weighting fraction. This tool successfully produced SOBPs within a depth range of 4-8 cm, 4-6 cm, and 5-7 cm. Comparison against a trial-and-error approach to creating SOBP by a different study shows that Linear Least Squares (lsqlin) approximation leads to a better SOBP.

1. Introduction

Delivering a precise and accurate dose to the target in radiotherapy is crucial. It ensures the maximum effectiveness of cancer treatment by providing the optimal radiation dose to the tumor, killing cancer cells, and preventing tumor growth or recurrence. As treatment precision improves, it also significantly reduces the risk of side effects by sparing surrounding healthy tissues and organs from unnecessary radiation. Sparing healthy tissue while effectively treating the tumor enhances treatment outcomes [1].

Proton therapy offers several theoretical advantages over conventional radiotherapy, primarily stemming from its unique physical properties and interaction with tissue [2]. At the core of these advantages is the proton beam's characteristic Bragg peak, which allows for superior dose distribution and more precise targeting of tumors [3]. This fundamental property enables proton therapy to deposit most of its energy at a specific depth in tissue, corresponding to the tumor's location.

The ability to adjust the depth dose in proton therapy is primarily achieved through the Spread-Out Bragg Peak (SOBP) technique. By selectively tweaking the intensity's weight and energy of individual proton beams, a flat uniform dose region is created that covers the desired treatment depth, effectively encompassing the entire tumor [4].

Obtaining an ideal SOBP is challenging. Achieving homogeneous dose distribution across the desired depth can be complex, as reported by a previous study showing that slightly tilted SOBPs might require correction [5]. The optimal parameters for creating a flat SOBP depend on various factors, including the combination beam energy available and the desired depth of the SOBP.

A previous study on proton pencil beam therapy for breast cancer was performed by Fasihu et al. [6]. In their research, the PHITS program simulated a proton pencil beam scanning for breast cancer, and the energy proton beams were set to 70-106 MeV with specified weighting to acquire SOBP for the depth target [6]. The pencil beam is fired into a mathematical phantom, and the delivered dose for cancer and organ at risk is calculated. The energy proton beam weighting was done by trial and error to cover the entire cancer with an even dose. This method hampers the reproducibility for similar cases, as a data-driven approach is preferred in simulation.

To avoid trial and error adjustments in producing the SOPB, this study aims to obtain the SOBP of proton pencil beams using Geant4 simulations and MATLAB optimization tool *Linear Least Squares* (lsqlin) to calculate its proper configurations. In this study, a water phantom was used to represent a breast. The energy of the proton beam imitates an actual device, Proteus®ONE. A slight variation of target depth was also conducted to assess the versatility of the MATLAB optimization tool in enabling the SOBP to be configured.

2. Methods

The steps of the methods in this study are shown in Fig. 1. Each step addresses the necessary setup and data acquisition required for the generation of SOBP. First, the Geant4 simulation was configured to accurately model the proton beam interactions. Next, each proton pencil beam's integral depth dose (IDD) was obtained. This IDD data was subsequently processed using the MATLAB lsqlin to calculate the optimal weighting fractions. Finally, the SOBP was generated based on these calculated weighting fractions.

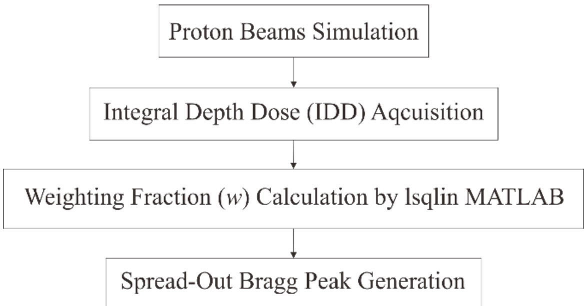


Fig. 1: Overview methodology

2.1. Proton Beams Simulation

The simulation uses a desktop computer with Ryzen 5 5600 processors, 16 GB DDR4 RAM, and Linux Mint 21.3 "Virginia" Operating System. The simulation was generated using Geant4 11.2.1 with the QGSP_BIC_HP simulation engine [7]. In this study, the proton pencil beam orientation and target depth imitate the study by Fasihu. Therefore, the SOBP configurations can be compared between trial-and-error methods against the proposed MATLAB optimization tool. The beam was fired from the lateral side of the right breast. The beam was set with a radius sigma of 4-5 mm [8]. The radius for each proton beam is shown in Table 1.

Table 1: Sigma radius for each proton beam

E Proton (MeV)	Sigma (mm)
70	5.00
72	4.92
74	4.81
76	4.72
78	4.63
80	4.54
82	4.47
84	4.41
86	4.34
88	4.27
90	4.21
92	4.15
94	4.10
96	4.05
98	4.00
100	3.94
102	3.88
104	3.82
106	3.75
108	3.70
110	3.64

The energy of the proton was set in the range of 70 MeV to 110 MeV with 2 MeV steps. This range of energy was chosen by considering a study of Bragg peak's range within therapeutic energy [9]. The target depth is designated at 4-8 cm from the skin. This target depth was chosen as the lowest available proton beam energy in this study; 70 MeV would deliver the optimum dose at a depth of 4 cm without any range compensator installed. An additional 4 cm from this depth also needed to be covered by SOBP. Hence, the target depth is 4-8 cm. The illustration of this orientation and target depth is shown in Fig. 2.

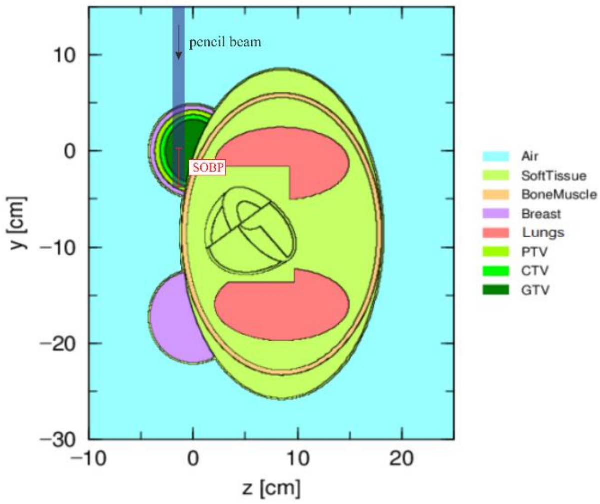


Fig. 2: Illustration of beam orientation and target depth [6]

For the simulation in this study, a water phantom with a size of 10 × 10 × 25 cm^3 was used to simulate breast tissue. Thinly sliced detectors at 10 × 10 × 0.01 cm^3 were lined up inside the water phantom to capture the acquired dose profile of each energy at different depth locations. For every proton beam simulation, 10^6 protons were fired towards the water phantom. The illustration of this simulation is shown in Fig. 3.

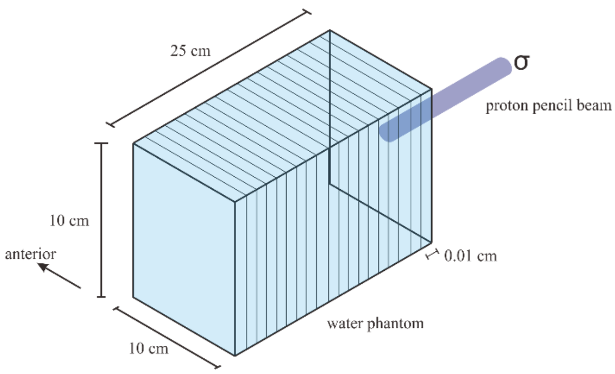


Fig. 3: Illustration of the water phantom in Geant4

2.2. Integral Depth Dose (IDD) Acquisition

The IDD represents the total dose on a normal plane to the beam's central axis along the depths. The IDD measured the entire dose deposition, including contributions from secondary particles for every slice depth of the water phantom, which fit the purpose of the thinly sliced detectors set in the water phantom in Fig. 3. A complete graph of IDD for every simulated proton beam is necessary to calculate weighting fraction and SOBP generation.

2.3. Weighting Fraction (w) Calculation by MATLAB Linear Least Squares (lsqlin)

The general form of the SOBP dose equation is typically expressed as

$$D_{tot}(z) = \sum_{i=1}^{f} w_i D_i(z) \quad (1)$$

Where $D_{tot}(z)$ represents the depth dose at z, w_i represents the weighting fraction for i-th pencil beam energy and $D_i(z)$ represents the depth dose of a pencil beam energy at z. Variable i and f are the given index for the pencil beams.

To treat breast cancer, the SOBP was created by targeting depths at 4-8 cm, 4-6 cm, and 5-7 cm for water phantom. The MATLAB lsqlin calculated appropriate weighting values to produce SOBP for the target depth. This tool utilizes the complete IDD of every proton beam. These three depth variations were assigned to evaluate the capability of MATLAB lsqlin to produce appropriate SOBP configurations.

The lsqlin function in MATLAB is designed to solve the following linear least squares problem with constraints. The problem formulation for this function is shown below.

$$|Cw - d|^2 \quad (2)$$

Where C is the coefficient matrix, w is the variable vector to be determined, and d is the target value. The solution to this problem must also satisfy

$$A \cdot w \leq b \quad (3)$$
$$Aeq \cdot w = beq \quad (4)$$
$$lb \leq w \leq ub \quad (5)$$

The MATLAB syntax for this study is shown below.

$$w = lsqlin(C, d, A, b, Aeq, beq, lb, ub) \quad (6)$$

where C is the coefficient matrix for the least squares problem, it must be minimized, d is a vector representing target values to approximate with a linear combination of the columns of C, parameter A is a matrix used to define linear inequality constraints, b is a right-hand side for the linear inequality constraints, Aeq is a matrix used to determine linear equality constraints, beq is the right-hand side of these linear equality constraints, lb and ub serve as lower bounds and upper bounds for the solution variables. These bounds set the minimum and maximum allowable values for the solution.

In this study, matrix C is the IDD data for each beam. Different data doses by each proton pencil beam energy are separated by column, and various depths are determined by row. Array d is the constraint optimization. Different values of this constraint would result in different SOBP configurations. This study requires a manual constraint value to acquire the flattest SOBP. The value of parameters A and b is empty, Array Aeq is set to one, and beq value to one. Array lb and ub are set to one. Eq. (6) results in the array w, which holds the appropriate weighting fraction for each proton beam energy.

2.4 Spread-Out Bragg Peak Generation

By applying weighting fraction and IDD to Eq. (1), a SOBP graph can be acquired. However, the weighting fraction is useful to simulate actual SOBP in Geant4. A simulation setup similar to the water phantom in Fig. 3 simulated SOBP. Instead of firing a single proton beam per simulation, in this SOBP simulation, every proton beam is fired sequentially. The weighting fraction calculates the number of fired protons for each energy proton beam. Each thinly sliced detector in the water phantom accumulated the absorbed dose by each proton beam.

3. Results and Discussion

The IDD graph for every single proton beam is shown in Fig. 4.

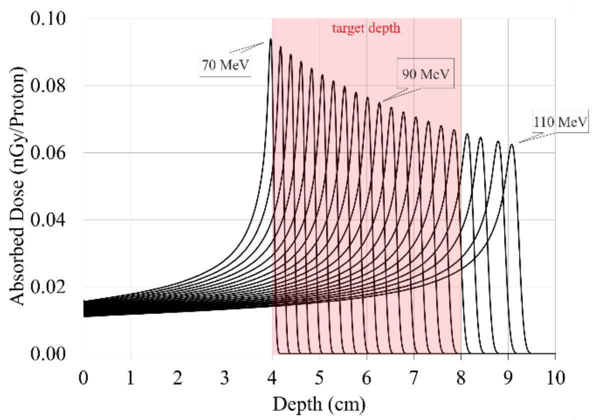


Fig. 4: IDD graph by single proton pencil beams of 70-110 MeV

A higher energy proton pencil beam would deliver a smaller dose peak and deeper depth for the same number of simulated protons. The proton pencil beam with an energy of 70 MeV produced its peak dose at a depth of 4 cm. Beams with energies ranging from 72 MeV to 102 MeV delivered their peak doses within the target depth. In comparison, beams with energies above 104 MeV overshot the target depth of 8 cm.

On the SOBP optimization process by the lsqlin function, the total value of w was set to 1. This would represent a percentage fraction for each value, which is 100%. The Lsqlin function requires a target vector or d constraint to calculate the optimization. This value is chosen at 0.0203 nGy/Proton for this depth as the flattest SOBP created. The optimized value of weighting fraction SOBP at 4-8 cm depth is shown in Table 2.

A bigger weighting fraction was assigned to the higher energy of the proton pencil beam. This was done because the dose at the deeper part of the target would only be reached by a higher energy proton beam, and the superficial part of the target was receiving the dose by multiple pencil beams. The exception applies to a pencil beam of 106 MeV as the dose peak by this beam wouldn't contribute to target depth. This exclusion was noticeable in Fig. 3 and the marginal value *w* for this proton pencil beam.

Table 2: Weighting fraction of SOBP by using MATLAB lsqlin function for the depth of 4-8 cm

E Proton (MeV)	Peak Dose at Depth (cm)	Weighting fraction
70	3.97	0.011
72	4.18	0.020
74	4.39	0.021
76	4.61	0.022
78	4.84	0.024
80	5.06	0.026
82	5.30	0.027
84	5.53	0.029
86	5.78	0.032
88	6.02	0.035
90	6.27	0.038
92	6.52	0.043
94	6.78	0.048
96	7.04	0.055
98	7.31	0.066
100	7.58	0.083
102	7.86	0.110
104	8.31	0.310
106	8.42	0
108	8.79	0
110	9.08	0

The SOBP can be created using Microsoft Excel by adding the dose of all the weighted pencil beams and normalizing it to the optimization constraint value. It is shown in Fig. 5.

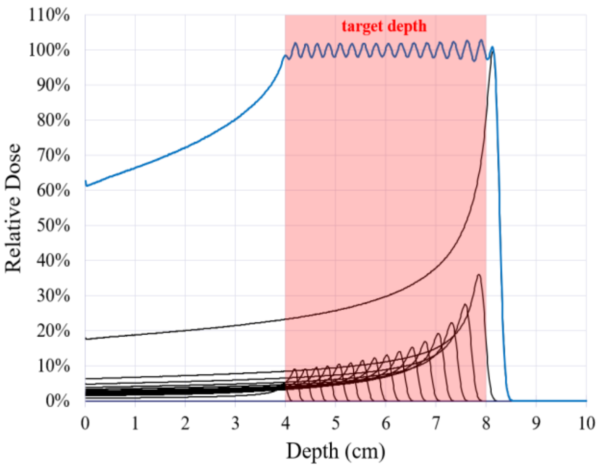


Fig. 5: Depth dose by weighted proton pencil beams as in Table 2 marked in a black line. The sum of these doses composes a depth dose of SOBP marked in a blue line.

The same weighting fractions were used in the Geant4 simulation to verify the result of these weighting fractions. The output of this simulation is compared to a previous study by Fasihu [6]. Their energy weight is modified to fit the proper comparison for this result. The energy weight is normalized into the weighting fraction. This is done using Eq. (7). Depth dose data normalized as the highest dose set to 104% relative dose. This is done to compensate for dose-exceedance imperfection. The complete modification is shown in Table 3, with the comparison of SOBP by MATLAB lsqlin and a previous study by Fasihu, as shown in Fig. 6.

$$\text{Weighting Fraction (w)} = \frac{\text{Energy Weight}}{\sum \text{Energy Weight}} \qquad (7)$$

Table 3: Modified Energy weight of SOBP by Fasihu for 4-8 cm target depth

E Proton (MeV)	Peak Dose at Depth (cm)	Energy Weight	Weighting fraction
70	3.97	0.5	0.013
72	4.18	0.6	0.015
74	4.39	0.7	0.017
76	4.61	0.8	0.020
78	4.84	0.9	0.022
80	5.06	1.0	0.024
82	5.30	1.2	0.029
84	5.53	1.3	0.032
86	5.78	1.4	0.034
88	6.02	1.4	0.034
90	6.27	1.6	0.039
92	6.52	2.0	0.049
94	6.78	2.0	0.049
96	7.04	2.1	0.051
98	7.31	3.0	0.073
100	7.58	3.4	0.083
102	7.86	5.0	0.122
104	8.31	12.0	0.294
106	8.42	0	0
108	8.79	0	0
110	9.08	0	0

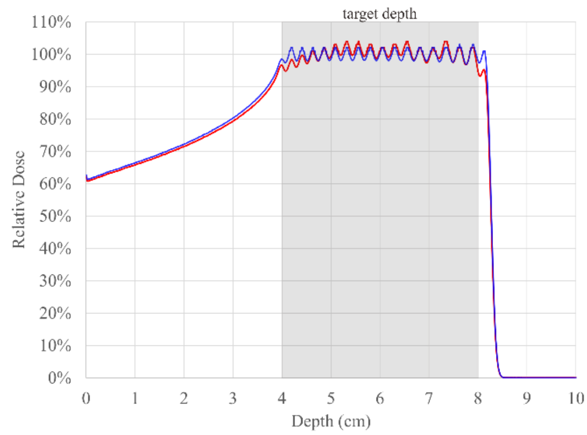


Fig. 6: Comparison of Generated SOBP. The blue line is the graph by MATLAB lsqlin optimization, and the red line is the graph of the previous study by Fasihu [6]

An overall flatter SOBP was achieved by applying the MATLAB lsqlin for weighting fraction. The delivered dose at the target depth is not perfectly even. The rippled dose is noticeable in Fig. 5, with a peak at 103% relative dose and a lower peak at 97% relative dose. The depth range of SOBP exceeds 8 cm by 0.31 cm. These imperfections are contributed by IDD single proton pencil beams whose dose peaks don't entirely cover the target depth. This would create a rippled SOBP dose as the MATLAB lsqlin attempts to cover the least dose difference against the target vector. The position of the IDD dose peak would dictate how the SOBP spreads. In this study, 2 MeV steps resulted in this rippled dose. In the case of dose overshoot, there is no IDD dose peak close enough to 8 cm depth. This would result in the next closest peak having to barge in the SOBP optimization, the 104 MeV proton pencil beam; hence, the SOBP exceeds 0.31 cm.

For the target depth of 4-6 cm, the same IDD is used to calculate the proper SOBP. The weighting fraction of lsqlin optimization and the simulated depth dose is shown in Table 4 and Fig. 7.

Table 4: Weighting fraction of SOBP by using MATLAB lsqlin function for the depth of 4-6 cm

E Proton (MeV)	Peak Dose at Depth (cm)	Weighting fraction
70	3.97	0.004
72	4.18	0.046
74	4.39	0.048
76	4.61	0.054
78	4.84	0.061
80	5.06	0.070
82	5.30	0.083
84	5.53	0.104
86	5.78	0.138
88	6.02	0.392
90	6.27	0
92	6.52	0
94	6.78	0
96	7.04	0
98	7.31	0
100	7.58	0
102	7.86	0
104	8.31	0
106	8.42	0
108	8.79	0
110	9.08	0

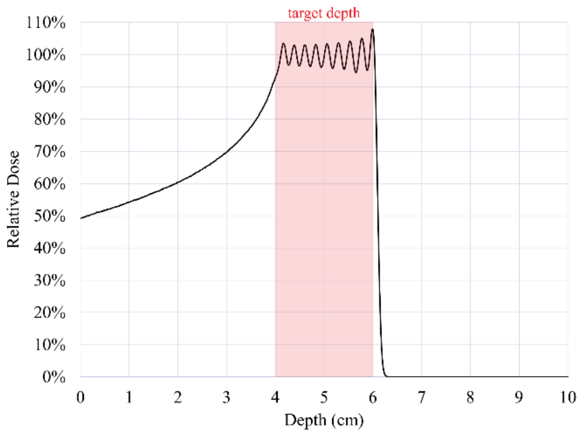


Fig. 7: Geant4 simulated SOBP configured by MATLAB lsqlin for target depth at 4-6 cm

A similar imperfection is noticeable for this SOBP despite no dose overshoot. The rippled dose was also observed for this depth, with the peak at 108% relative dose and the lower peak at 95% relative dose. By taking note of Table 4, the MATLAB lsqlin managed to selectively filter out unnecessary proton beams whose peak doses were not within the depth target.

Another SOPB for a 5-7 cm target depth is also calculated. The result is shown in Table 5 and Fig. 8.

Table 5: Weighting fraction of SOBP by using MATLAB lsqlin function for the depth of 5-7 cm

E Proton (MeV)	Peak Dose at Depth (cm)	Weighting fraction
70	3.97	0
72	4.18	0
74	4.39	0
76	4.61	0
78	4.84	0
80	5.06	0.035
82	5.30	0.049
84	5.53	0.054
86	5.78	0.061
88	6.02	0.071
90	6.27	0.084
92	6.52	0.105
94	6.78	0.136
96	7.04	0.405
98	7.31	0
100	7.58	0
102	7.86	0
104	8.31	0
106	8.42	0
108	8.79	0
110	9.08	0

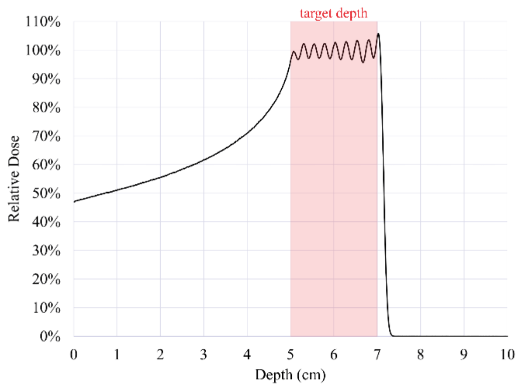


Fig. 8: Geant4 simulated SOBP configured by MATLAB lsqlin for target depth at 5-7 cm

A similar imperfection is also noticeable for this simulated SOBP. Regardless of the depth variance, the MATLAB lsqlin continued to manage the proper weighting fraction.

This study's weighting fraction of the proton beam is not universally applicable, as different target depths require different beams' energy to deliver the optimum dose. However, the universal aspect lies in using MATLAB's lsqlin to generate optimal weighting fractions based on available proton beams.

Suggestions are provided in this study to guide future research on generating SOBP. Weighting fraction by lsqlin MATLAB needs to be investigated regarding the planar dose distribution as proton scattered by multiple coulomb interactions. To generate a flatter SOBP, adding additional variance to the proton beam's energy by applying smaller energy steps, such as 1 MeV or 0.5 MeV, should give a smaller dose ripple on SOBP. As the proton beam's energy changed, the peak dose depth also changed.

An increased number of dose peaks at the target depth would be useful as lsqlin is optimizing to cover the entire depth with minimum dose disparity.

Fine-tuning the dose depth range of SOBP can be done by composing specific energy of proton pencil beams with the peak depth dose precisely at the depth target. A proton Bragg peak range data set would help determine the appropriate proton energy [10]. Another way to adjust the depth dose without modifying the proton pencil beam energy is by using range modulators. A 3D-printed range modulator has been tested to work well [11]. Another study used homogeneous water equivalent materials to create printable bolus [12]. A custom-made bolus using silicone rubber is also shown to be a prospective alternative [13]. It is worthwhile to implement or simulate any adjustments inspired by these studies.

4. Conclusion

This study successfully generated Spread-Out Bragg Peaks (SOBP) for breast cancer treatment using proton pencil beam Monte Carlo simulations in Geant4 by utilizing proton beam energies ranging from 70 to 110 MeV. The Linear Least Squares (lsqlin) optimization tool effectively configured proton beam weighting fractions, producing SOBPs across various depth ranges. Despite this attainment, some imperfections were observed in the dose distribution, including dose ripples and minor dose deviations beyond the target depth. Nevertheless, the lsqlin approach demonstrated improved SOBP configuration compared to trial-and-error methods used by another study.

References

[1]. G. Prasanna, K. Rawojc, C. Guha, J. C. Buchsbaum, J. U. Miszczyk, and C. N. Coleman, "Normal Tissue Injury Induced by Photon and Proton Therapies: Gaps and Opportunities" International Journal of Radiation Oncology Biology Physics, 110(3), 1325-1340, (2021).

[2]. R. Mohan, "A review of proton therapy - Current status and future directions" Precision Radiation Oncology, 6(2), 164-176, (2022).

[3]. M. Pennock, S. Wei, C. Cheng, H. Lin, S. Hasan, A. M. Chhabra, J. I. Choi, R. L. Bakst, R. Kabarriti, C. B. Simone II, N. Y. Lee, M. Kang, and R. H. Press, "Proton Bragg Peak FLASH Enables Organ Sparing and Ultra-High Dose-Rate Delivery: Proof of Principle in Recurrent Head and Neck Cancer" Cancers, 15(15), (2023).

[4]. G. Lattery, T. Kaulfers, C. Cheng, X. Zhao, B. Selvaraj, H. Lin, C. B. Simone II, J. I. Choi, J. Chang, and M. Kang, "Pencil Beam Scanning Bragg Peak FLASH Technique for Ultra-High Dose Rate Intensity-Modulated Proton Therapy in Early-sStage Breast Cancer Treatment" Cancers, 15(18), (2023).

[5]. D. Jette and W. Chen, "Creating a spread-out Bragg peak in proton beams" Physics in Medicine and Biology, 56(11), (2011).

[6]. M. F. K. Fasihu, A. W. Harto, I. M. Triatmoko, G. S. Wijaya, and Y. Sardjono, "Radiation dose optimization of breast cancer with proton therapy method using particle and heavy ion transport code system" Jurnal Teknologi Reaktor Nuklir Tri Dasa Mega, 23(2), 79, (2021).

[7]. J. Allison, K. Amako, J. Apostolakis, P. Arce, M. Asai, T. Aso, E. Bagli, A. Bagulya, S. Banerjee, G. Barrand, B. R. Beck, A. G. Bogdanov, D. Brandt, J. M. C. Brown, H. Burkhardt, Ph. Canal, D. Cano-Ott, S. Chauvie, K. Cho, G. A. P. Cirrone, and H. Yoshida, "Recent developments in GEANT4" Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 835, 186-225, (2016).

[8]. S. Safai, C. Bula, D. Meer, and E. Pedroni, "Improving the precision and performance of proton pencil beam scanning" Translational Cancer Research, 1(3), 196-206, (2012).

[9]. S. Zarifi, H. T. Ahangari, S. B. Jia, M. A. Tajik-Mansoury, M. Najafzadeh, and M. P. Firouzjaei, "Bragg peak characteristics of proton beams within therapeutic energy range and the comparison of stopping power using the GATE Monte Carlo simulation and the NIST data" Journal of Radiotherapy in Practice, 19(2), 173-181, (2020).

[10]. H. Freitas, P. Magalhaes Martins, T. Tessonnier, B. Ackermann, S. Brons, and J. Seco, "Dataset for predicting single-spot proton ranges in proton therapy of prostate cancer" Scientific Data, 8(1), (2021).

[11]. F. Horst, E. Beyreuther, E. Bodenstein, S. Gantz, D. Misseroni, N. M. Pugno, C. Schuy, F. Tommasino, U. Weber, and J. Pawelke, "Passive SOBP generation from a static proton pencil beam using 3D-printed range modulators for FLASH experiments" Frontiers in Physics, 11, (2023).

[12]. H. Lin, C. Shi, S. Huang, J. Shen, M. Kang, Q. Chen, H. Zhai, J. McDonough, Z. Tochner, C. Deville, and C. B. Simone II, "Applications of various range shifters for proton pencil beam scanning radiotherapy" Radiation Oncology, 16(1), (2021).

[13]. H. Sutanto, I. Marhaendrajaya, G. W. Jaya, E. Hidayanto, A. S. Supratman, S. Y. Astuti, T. Budiono, and M. A. Firmansyah, "The Properties of Bolus Material using Silicone Rubber" IOP Conference Series: Materials Science and Engineering, (2019).