Atom Indonesia

Journal homepage: http://aij.batan.go.id

Dose Planning Evaluation of Intensity-Modulated Proton Therapy (IMPT) Technique Based on In-House Dynamic Thorax Phantom

V. Vernanda, A. Azzi, S. A. Pawiro*

Department of Physics, Faculty of Mathematics and Natural Science, University of Indonesia, Depok, West Java, 16424, Indonesia

ARTICLE INFO

Article history:
Received 27 October 2021
Received in revised form 14 September 2022
Accepted 10 October 2022

Keywords:

NSCLC
IMPT
Treatment planning
Bragg-peak
IMRT
TPS

ABSTRACT

One of the drawbacks of the Intensity Modulated Radiation Therapy (IMRT) technique is that the absorbed dose in healthy tissue is relatively high. Proton beam has characteristics that can compensate for these drawbacks. The Bragg peak characteristic of a proton beam allows the administration of high radiation doses to the target organ only. Non-Small Cell Lung Cancer (NSCLC) cases are located in the vicinity of many vital organs, so radiation doses that exceed a certain limit will have a significant impact on these organs. Proton is a heavy particle that exhibits interaction patterns with tissue heterogeneity that differ from that of photon. This study aims to determine the distribution of proton beam planning doses in the NSCLC cases with the Intensity Modulated Proton Therapy (IMPT) technique and compare its effectiveness with the IMRT technique. Treatment planning was done by using TPS Eclipse on the water phantom and on the in-house thorax dynamic phantom. The water phantom planning parameters used are one field at 0° and three fields at 45°, 135°, and 225°. In this study, a single, sum, and multiple field techniques on the in-house thorax dynamic phantom were used. The evaluation was performed by calculating Conformity Index (CI), Homogeneity Index (HI), and Gradient Index (GI) parameters for each treatment planning. As a result, a bit of difference in the CI the HI values are shown between IMPT and IMRT planning. The GI values of IMPT planning are in the range between 4.15-4.53, while the GI value of IMRT is 7.89. The histogram results of the planar dose distribution show that the IMPT treatment planning provides fewer off-target organ doses than the IMRT planning. Evaluation was also carried out on the IMPT treatment planning of target organs in five areas of interest and four OAR positions. The evaluation results were then compared with the IMRT measurement data. As a result, the value of the point doses at the target organ did not differ significantly. However, the absorbed dose with the IMPT technique at four OAR positions is nearly zero, which had a large difference compared to the IMRT technique.

INTRODUCTION

About 85 % of lung cancer cases are Non-Small Cell Lung Cancer (NSCLC) [1]. Treatment of lung cancer can be done with surgery, chemotherapy, and radiotherapy. For the NSCLC type, treatment can be done by one or a combination of these methods.

One of the newest techniques used in radiotherapy is Intensity Modulated Radiation Therapy (IMRT). This technique uses multiple intensity-modulated beams. As a result, the dose conformity will be better and allow for precise beam shaping according to the target organ geometry. One of the characteristics of the photon beam is high depth dose distribution near the surface. The peak of dose deposition occurs not far from the surface that receives the irradiation dose and then decreases exponentially with increasing depth [2,3]. This characteristic results in the dose being deposited along the path of the photon beam in the surrounding healthy tissues. Lung cancer cases are surrounded by several healthy organs, such as the heart, spine, and parts of the lung that are not affected by cancer [4]. So, photon beams do not

*Corresponding author.
E-mail address: supriyanto.p@sci.ui.ac.id
DOI: https://doi.org/10.55981/aij.2023.1196

fully provide the minimum dose to healthy tissue. Another modality in radiotherapy is proton therapy, which uses proton beams. A proton beam has a characteristic called the Bragg peak, which occurs when a proton beam hits a target, leaving minimal dose deposition along its path. In the case of lung cancer, the characteristic Bragg peak allows for the minimum dose deposition of the healthy organs around the cancerous tissue [2].

The latest radiotherapy technique with proton beams is Intensity Modulated Proton Therapy (IMPT), also known as proton pencil beam therapy. The intensity of the pencil beam can be optimized to obtain a conformal dose distribution that follows the target volume [4]. The monoenergetic narrow proton beam is then scanned layered on the target volume magnetically in a zigzag pattern [5]. Research conducted by Huang et al. showed that by using the IMPT technique, the volume of lungs receiving radiation doses of more than 20 Gy was 24.3 %, lower than the previous proton technique used, which was 35.5 % [6]. Another research conducted by Kase et al. shows that by using the IMPT technique, the near-maximum doses to the skin were decreased to an average of 64 % with the same beam angles compared with the previous proton technique [7]. Research about the comparison of dose distribution with IMPT was also conducted by Zhang et al. While keeping the PTV coverage similar, the spinal cord was clearly spared using a curved dose distribution, which is a characteristic of IMPT, without compromising the PTV coverage than the previous technique. Zhang et al. also compared the IMPT with IMRT, while keeping the PTV coverage similar, IMPT spared more of the lung (19.8 % mean absolute improvement in total volume of lung receiving at least 5 Gy [V5]), heart (14.2 % mean absolute improvement in heart V40), esophagus (6.8 % mean absolute improvement in esophageal V55), and spinal cord (9.5 Gy mean absolute improvement in spinal cord maximal dose) than IMRT did [8].

Based on its characteristics, proton beam radiotherapy has the potential to treat lung cancer. This study was conducted to determine the distribution of radiotherapy treatment planning doses using the IMPT technique and to compare it with the planning and measurement using the IMRT technique in simulated lung cases. An Eclipse Treatment Planning System (TPS) and dynamic thorax phantom were both used in this study. The conformity index (CI), homogeneity index (HI), and gradient index (GI) of proton radiotherapy planning data were compared with planning and measurement results with the IMRT technique obtained from previous studies.

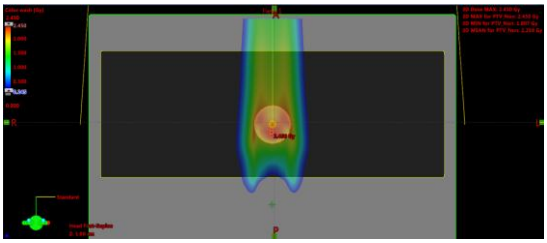
METHODOLOGY

Treatment planning with virtual water phantom

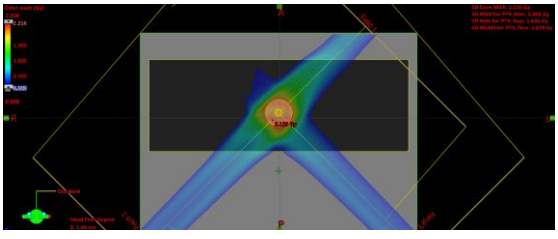
Two virtual water phantoms with dimensions of 30 cm × 30 cm × 30 cm were made with TPS Eclipse ver. 13.6 (Varian Medical System, USA). For optimization, the TPS is equipped by PCS (Proton Convolution Superposition) 15.6.03 and NUPO (Nonlinear Universal Proton Optimizer) 15.6.03. The first phantom has a homogenous water density. The second phantom, a cubic with the dimension of 28 cm × 30 cm × 30 cm, which has a density equal to the density of a lung structure, was put at 5 cm depth. For both phantoms, a sphere that represents the target organ with a diameter of 3 cm was placed at 7 cm depth. Details of the treatment planning are shown in Table 1. and Fig. 1.

Table 1. Treatment planning parameter with virtual water phantom.

Water Phantom	Number of Field	Gantry Angle (^{o})	Variation
Homogeny	1	0^{o}	With optimization Without optimization
Inhomogeny	1	0^{o}	-
	3	45^{o}	-
		135^{o}	-
		225^{o}	-



(a)



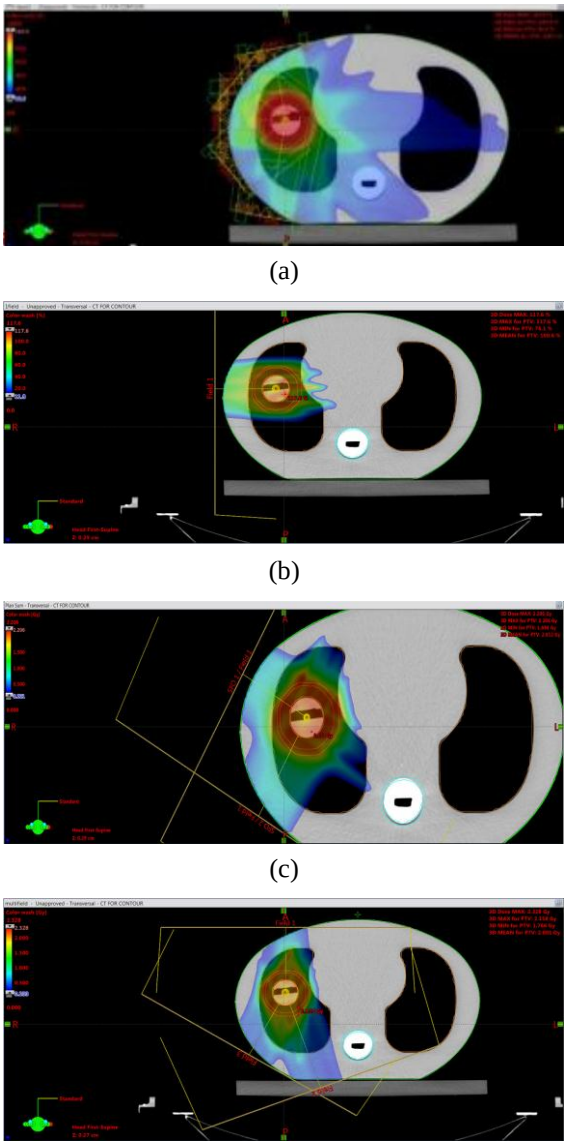
(b)

Fig. 1. The illustration of treatment planning for IMPT in homogenous (a) and inhomogeneous phantoms (b).

Treatment planning with ct image of in-house dynamic thorax phantom

In-house Dynamic thorax phantom image data was taken from Putranto et al [9]. The data

transferred into a computer were then performed contouring for PTV, lung volume, and OAR sections consisting of the spinal cord, heart, and lungs. The treatment planning was done with three variations; a single field, a summation of two single fields, and multiple fields. Details of the field arrangement are shown in Table 2. and Fig. 2**.** The treatment planning evaluation was done by calculating the evaluation parameters such as Conformity Index (CI), Homogeneity Index (HI), and Gradient Index (GI). Point doses have been measured at five points on the target organ and four points on the spinal cord. Point-dose measurement was performed by measuring the pixel value of the exported target organ plan dose with ImageJ software. The result of the point-dose measurement of each plan was compared with the experimental data.



(a) (b) (c) (d)

Fig. 2. Illustration of treatment planning for in-house thorax phantom with IMRT (a), IMPT-1 (b), IMPT-2 (c), and IMPT-3 (d) techniques.

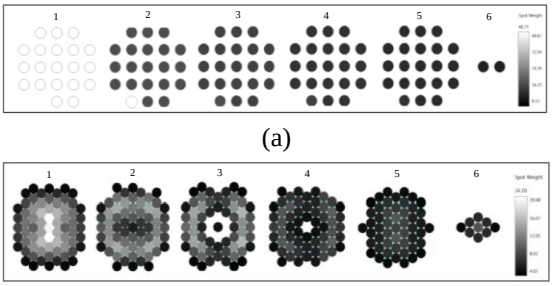
Table 2. Treatment planning parameters with in house dynamic thorax phantom.

Code	Technique	Number of Field	Gantry Angle
IMPT-1	IMPT	1	300^o
IMPT-2	IMPT	2	180^o, 210^o
IMPT-3	IMPT	3	0^o, 160^o, 210^o

RESULTS AND DISCUSSION

Treatment planning with virtual water phantom

The spot weight difference between virtual water phantom with and without optimization is presented in Fig. 3. The difference can be seen in the color distribution of each layer. The image without optimization has a spot with the same degree of blackness, while the one with optimization shows variation in each layer's color. This difference occurs because weighting is carried out according to the desired dose distribution on the target during planning optimization. This weighting causes intensity modulation that does not happen in treatment planning without optimization.



(a) (b)

Fig. 3. Spot weight difference for each layer of non-optimized 190 planning (a) and optimized planning (b) with homogeny virtual water phantom.

Treatment planning evaluation results with dynamic thorax phantom

Dose distributions of each planning are presented in Fig. 4. It can be seen that target organ coverage with the IMPT technique is better than IMRT. These findings are in line with other experiments, for example, conducted by Huang et al. [6]. Their experiment shows that irradiated volume outside the target organ with the IMRT technique is greater than the IMPT technique.

The evaluation was performed by calculating CI, HI, and GI parameters for each plan. Comparison of each parameter is presented in Table 3. It can be seen that the CI and HI values of

each treatment plan are slightly different. The results of the CI value are in line with experimental results carried out by Chi et al. [10]. Their work shows that CI values for IMPT are slightly lower than 1. It means that not all target volumes receive prescribed doses, because the proton beam has a bigger lateral penumbra than electron beam. In addition, the interaction of protons with matter depends on the density of the matter. In this case, the protons travel through different densities. The difference in HI value between the current work and the Chi et al. works is only 1 %. This small difference between IMPT and IMRT treatment planning shows that both techniques give the same quality of conformity and homogeneity. However, the GI value between IMRT and IMPT techniques has a significant difference.

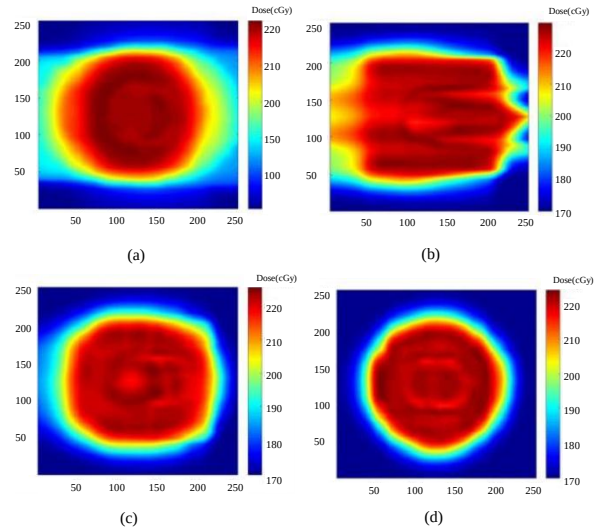


Fig. 4. Dose distribution of a target with IMRT (a), IMPT-1 (b), IMPT-2 (c), and IMPT-3 (d) techniques.

Table 3. Comparisons of CI, HI and GI parameters for each treatment planning.

Structure	IMRT	IMRT-1	IMPT-2	IMPT-3
Cl	1	0.91	0.98	0.98
HI	1.07	1.95	1.11	1.08
GI	7.89	4.31	3.15	4.53

The GI values represent the steeper dose reduction outside the target. The IMPT has a steeper dose reduction than the IMRT because of its Bragg peak characteristic of protons. This indicates that the off-target dose distribution with IMPT is smaller than that of IMRT. The area covered by the dose was less in planning with IMPT than with the IMRT. It is also reduced by using more fields in IMPT planning. This result is in line with the GI value.

The OAR dose structure for each planning is presented in Table 4**.** The results show that the OAR dose from each planning was still below a certain limit, but the IMPT technique provided a lower OAR dose than IMRT. These results agree with the results undertaken by Huang et al. [6] shows the V20 for lungs is reduced from 38.4 % to 24.3 % with the IMPT technique.

Table 4. OAR structure doses for each treatment planning.

Structure	Dose Constraint	IMRT	TP-1	TP-2	TP-3
Lung	V20 (%)	17.3	9.1	13.1	15.6
Spinal Cord	Dmaks (cGy)	38.7	0	0.3	0.5
Heart	V25 (%)	0	0	0	0

Point dose on the target and the spinal cord

The doses at five points on the target and four points on the spinal cord are presented in Table 5 and Table 6. There is a huge dose discrepancy between each point position on target with IMPT-1 planning. The discrepancy decreases as more fields are used. This indicates that the more fields give more conformity on the target organ, the result is in line with our CI value. The point dose on the spinal cord with IMPT is nearly zero. The points on the spinal cord do not receive a significant radiation dose. The dose on the spinal cord is minimal, only 0.3 cGy, and it is not on the measurement point. This shows that proton therapy, in particular the IMPT, has a steeper dose reduction than IMRT.

Table 5. Point dose on target.

Target Point	Dose (cGy)			
	IMRT	IMPT-1	IMPT-2	IMPT-3
RL	207.2	230.69	214.54	197.6
LL	203.7	225.69	204.91	196.16
S	199.4	211.42	207.87	205.55
I	186.3	**222.11**	211.81	202.37
C	204.8	209.79	194.95	204.88

Table 6. Point dose on spinal cord.

OAR Area	Dose (cGy)			
	IMRT	IMPT-1	IMPT-2	IMPT-3
1	11.23	0	0	0
2	26.73	0	0	0
3	1.51	0	0	0
4	5.25	0	0	0

CONCLUSION

The conformity and homogeneity of IMPT are as good that of IMRT. The GI values of the IMPT treatment planning are 4.13, 4.15, and 4.53, and the IMRT treatment planning is 7.69. This value indicates that IMPT has a steeper dose reduction than IMPT, leading to a lower off-target dose distribution. Therefore, IMPT also reduces the probability of secondary cancer. It can be concluded from this experiment that IMPT is a better treatment technique for lung cancer than IMRT.

ACKNOWLEDGMENT

This study is funded by research grant Universitas Indonesia PUTI 2020 with contract number NKB951/UN2.RST/HKP.05.00/2020.

AUTHOR CONTRIBUTION

V. Vernanda, A. Azzi, and S. A. Pawiro equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

REFERENCES

1. C. S. dela Cruz, L. T. Tanoue and R. A. Matthay, Clin. Chest. Med. **32** (2011) 605.
2. T. Mitin and A. L. Zietman, J. Clin. Oncol. **32** (2014) 2855.
3. K. -S. Baumann, V. Flatten, U. Weber *et al*., Radiat. Oncol. **14** (2019)183.
4. S. Mesko and D. Gomez, Curr. Treat. Options in Oncol. **19** (2018) 76.
5. W. Schlegel, T. Bortfeld and A. Grosu, New Technologies in Radiation Oncology, Springer (2006) 459.
6. Q. Huang, S. K. Jabbour, Z. Xiao *et al.*, Radiat. Oncol. **13** (2018) 78.
7. Y. Kase, H. Yamashita, H. Fuji *et al.*, J. Radiat. Res. **53** (2012) 272.
8. X. Zhang, Y. Li, X. Pan *et al*., Int. J. Radiat. Oncol. Biol. Phys. **77** (2010) 357.
9. T. Cao, Z. Dai, Z. Ding *et al.*, Precis. Radiat. Oncol. **3** (2019) 72.
10. A. Chi, L. Lin, S. Wen *et al*., Radiat. Oncol. **12** (2017) 132.