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Dose Analysis of Boron Neutron Capture Therapy (BNCT) for Breast Cancer Based on Particle and Heavy Ion Transport Code System (PHITS) V.3.34

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A B S T R A C T

Breast cancer is one of the most common types of cancer, with a high incidence and mortality rate worldwide, including in Indonesia. Boron Neutron Capture Therapy (BNCT) has been formulated as a promising method of radiation therapy in the treatment of breast cancer due to its ability to deliver high doses to target lesions with minimal damage to healthy tissue. This study aims to analyze the BNCT dose in breast cancer and evaluate the irradiation time in two directions: anterior-posterior (AP) and left lateral (LLAT). This research utilizes the PHITS version 3.34 simulation tool to define the geometry of breast cancer, the surrounding organs, and the radiation sources used. The phantom used was an ORNL adult woman with a 2 cm tumor. The neutron source was an accelerator with a 30 MeV proton beam. Boron concentrations were 30, 60, 90, 120, and 150 μg/g of cancer tissue. This research shows that the higher the boron concentration, the shorter the irradiation time required, thereby minimizing side effects and the risk of damage to Organ at Risk (OARs). For the AP irradiation technique, the resulting irradiation times were 27.62 minutes, 16.14 minutes, 13.12 minutes, 11.05 minutes, and 9.54 minutes. Meanwhile, in the LLAT direction, the resulting times were 135.23 minutes, 113.46 minutes, 78.23 minutes, 59.70 minutes, and 48.27 minutes. A boron concentration of 150 μg/g was chosen as the optimal concentration in this simulation because it results in a short irradiation time from each irradiation direction and ensures a safe dose for Organs at Risk (OARs). In the AP irradiation technique, the dose absorbed by the skin was 0.46 Gy, the ipsilateral lung was 1.01 Gy, the contralateral lung was 0.16 Gy, the ribs were 0.61 Gy, and the heart was 0.11 Gy. Meanwhile, in the LLAT irradiation technique, the dose absorbed by the skin was 1.03 Gy, the ipsilateral lung was 2.19 Gy, the contralateral lung was 0.72 Gy, the ribs were 1.62 Gy, and the heart was 0.40 Gy.

1. INTRODUCTION

Cancer is one of the most common health issues, with almost 20 million new cases and 9.7 million deaths reported in 2022. In Indonesia, 396,914 new cases and 234,511 deaths due to cancer were recorded in the same year [1], with the growth rate of cases increasing by 1.73% in the last two years [1, 2]. Breast cancer is the most common type of cancer, with 2.3 million new cases and 666 thousand deaths globally, as well as 66,271 new

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cases and 22,598 deaths in Indonesia in 2022 [1]. It is projected that by 2040, the number of new cases of breast cancer will exceed 3 million, and deaths will reach 1 million [3].

Breast cancer often occurs in lobules or ducts [4]. Symptoms can include a lump or thickening in the breast, changes to its shape or size, and abnormal discharge from the nipple [5]. Early detection is critical and can be achieved through screening methods such as CT, MRI, mammography, thermography, and ultrasonography [4], as well as FDG-PET/CT, which is more effective for early-stage cancer [6]. The commonly used treatment methods are surgery and chemotherapy, although they are less effective due to significant side effects [7]. New radiotherapy methods such as (Boron Neutron Capture Therapy) BNCT, Proton Beam Therapy, Fast Neutron Therapy, X-Ray Therapy, and Carbon Ion Therapy are being developed. BNCT is the most promising new radiotherapy method because it can minimize damage to healthy tissue [8]. The BNCT treatment mechanism is illustrated in Fig. 1.

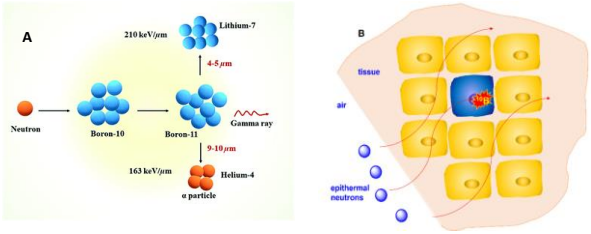

Fig. 1. (A): Neutron capture by ^{10}B and fission reaction of ^{11}B [9]; (B): thermalization of neutron and destruction of selective cancer cells [10]

BNCT is a radiation therapy that uses alpha and ^{7}Li particles from the $^{10}B(n, \alpha)^{7}Li$ nuclear fission reaction to kill cancer cells [11]. Alpha particles have high LET values and short ranges [12], so energy is deposited only in individual cells [9, 11]. BNCT is superior to proton therapy in delivering large doses to the target lesion with minimal damage to healthy tissue [13] and has milder side effects than conventional therapy and chemotherapy [14]. Figure 2 shows the effectiveness of BNCT compared to other radiation therapies. BNCT can selectively target tumor cells by providing minimal radiation effects on healthy tissue before and after radiation. The main challenge of BNCT is delivering Boron compounds to tumors without excessive uptake in normal tissue [11].

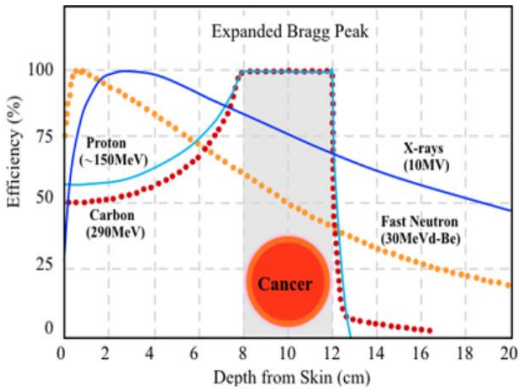

Fig. 2. Effectiveness of BNCT [15]

In BNCT, accelerator neutron sources are more effective than reactor-based neutron sources [16]. The fast neutron beam generated by the accelerator is moderated into thermal or epithermal neutrons that can be used for BNCT by the Beam Shaping Assembly (BSA) collimator. The BSA can convert the proton beam produced by the cyclotron into neutrons through interactions between the protons and the target, such as lithium or beryllium [17]. There are two boron carrier compounds in BNCT, Sodium Borocaptate (BSH) and ^{10}B-p-boronophenylalanine (BPA) [18]. The accuracy of BNCT depends on the dose administered. Dosing in BNCT involves alpha, boron, neutron, and proton doses [19]. The simulation program used is (Particle and Heavy Ion Transport code System) PHITS to determine the accuracy of the dose.

PHITS is a general-purpose Monte Carlo radiation transport code used to simulate the behavior of various particle species with energies up to 1 TeV per nucleon for ions [20]. PHITS can be used to calculate mean dose and 3D dose distribution, as well as provide better dose estimates and accurate projections of patient-absorbed dose [21].

This study analyzed the BNCT dose in breast cancer using PHITS version 3.34 based on the results of previous studies. Fujimoto et al. first reported the use of BNCT for recurrent breast cancer in the left axilla with neutron irradiation from the front and back of the left axilla [22, 23]. Pramusinta et al. conducted a study using MCNPX to analyze the irradiation time in breast cancer treatment with boron concentrations ranging from 70 to 150 µg/g. Their findings indicated that the shortest irradiation time, 4 hours and 15 seconds, was achieved at the highest boron concentration of 150 µg/g [24]. Yeom et al. found that PHITS had the fastest initiation time compared to MCNP6 and Geant4 [25].

Previous research was carried out using neutron irradiation from the front and back of the left hand. These limitations in the radiation direction can ignore the effects of radiation from other angles,

which may be more effective or reduce the dose received by healthy organs. Previous BNCT research used a simulation device that produced quite long irradiation times. Long-lasting irradiation procedures can cause physical and psychological discomfort in patients, including fatigue. In addition, long irradiation times can increase the risk of damage to healthy tissue, such as damage to the skin. Long duration of irradiation can also reduce the effectiveness of treatment. So, this problem becomes a reference for further research to analyze the BNCT dose in breast cancer using two irradiation techniques, namely AP and LLAT, to determine the most effective direction of radiation in delivering the dose to cancer tissue while minimizing radiation exposure to healthy organs. The simulation program used is PHITS version 3.34 because of its superiority in initiation speed and calculation accuracy.

2. METHODOLOGY

The instrumentation used to run a series of simulations in this research includes:

1. A portable computer with the following specifications: Intel(R) Pentium(R) Gold 7505 @2.00GHz processor, 8 GB RAM, and a Windows 11 Home Single Language 64-bit Operating System.
2. PHITS simulation program version 3.41.
3. Microsoft Word 2021.
4. Microsoft Excel 2021.
5. Notepad++.
6. Ghostscript.
7.

2.1 Patient Model

The patient model uses geometric modeling based on the Oak Ridge National Laboratory (ORNL) adult female phantom model and body composition data from Report 145 of the International Commission on Radiological Protection (ICRP). The phantom program code is referred to from the research results of Krstic and Nikezic (2007). It was written with the MCNP-4B program and then converted into input in the PHITS simulation. These codes are adapted to the needs of the research model. The organs created in this research are breasts, lungs, heart, spine, ribs, and skin.

The modelled breast cancer is a case of breast cancer at the National Taiwan University Hospital, at stage I, with a diagnosis of T1N0M0, which shows a small tumor with a diameter of 2 cm without distant metastasis or spread to the lymph nodes. The cancer was located in the left breast with a CTV to skin distance of 2 cm [26]. In a treatment planning system (TPS) used for dose planning for patients, there are three target volumes: Gross Target Volume (GTV), Clinical Target Volume (CTV), and Planning Tumor Volume (PTV) [27]. According to the 2018 national guidelines for medical services for breast cancer management of the Indonesian Ministry of Health, the distance between GTV and CTV is 0.5 cm, while the distance between CTV and PTV is 0.5 to 1 cm [28]. The simulation results were referenced using FDG-PET/CT data for breast cancer obtained from the School of Medicine at the Aristotle University of Thessaloniki and Papageorgiou General Hospital in Thessaloniki, Greece [29]. The results of visualizing the 2-dimensional shape of breast cancer geometry can be seen in Fig 4.

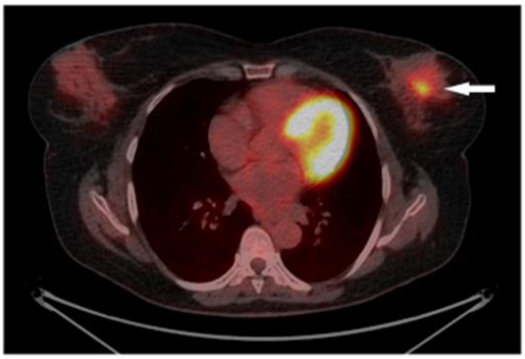

Fig. 3. Transverse 18F-FDG PET/CT images in patients with breast cancer

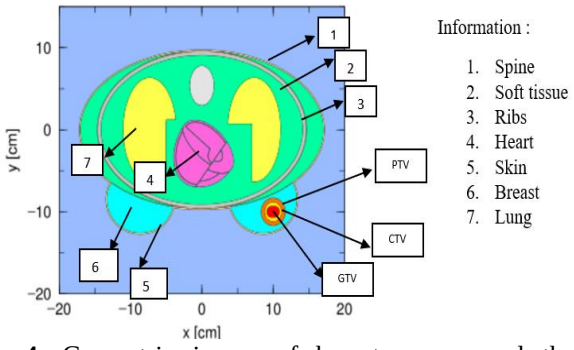

Fig. 4. Geometric image of breast cancer and the surrounding tissue

2.2 Neutron Source

This research used the HM-30 1 mA cyclotron accelerator from Sumitomo Heavy Industries, which produces a 30 MeV proton beam [30]. The depiction of the BSA collimator in Fig. 5 in this study results from replicating the optimization carried out by I Made Ardhana [31]. A BSA collimator generates a suitable neutron flux for the BNCT. The neutron flux output results are shown in Table 1.

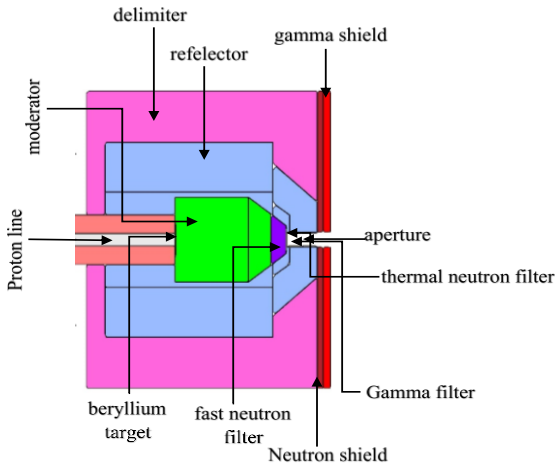

Fig. 5. BSA collimator design

Table 1. BSA output results with ORNL phantom

Parameter	IAEA Recommendations	Optimization Results
Epithermal Neutron Flux (n/cm^{2}s)	>1.0 × 10^9	1.7 × 10^9
Fast Neutron Dose Rate/Epithermal Neutron Flux (Gy-cm^2/n)	<2.0 × 10^{-13}	1.3 × 10^{-13}
Gamma Dose Rate/Ephitermal Neutron Flux (Gy-cm^2/s)	<2.0 × 10^{-13}	1.6 × 10^{-13}
The ratio of Thermal and Epithermal Neutron Flux (ϕ_{th}/ϕ_{epi})	<0.05	0.04
The Ratio of Neutron Current and Neutron Flux (J/ϕ_{epi})	>0.7	0.9

Table 1 shows the BSA output results with the ORNL phantom compared with IAEA recommendations for various neutron flux and dose rate parameters. The optimization results show that the results meet the IAEA's recommendations.

2.3 Dosimetry

Four dose components are considered in the core reaction of BNCT: gamma dose, boron dose, neutron dose, and proton dose. The dose rate values for these four components are obtained from the PHITS output and then processed using Microsoft Excel to calculate the equivalent dose rate, irradiation time, and equivalent dose.

a. Dose Rate Calculation

The total dose rate or equivalent dose rate is obtained from the sum of the dose rates from each source multiplied by the irradiation quality factor from the radiation source, as shown in Table 2. The total dose rate can be calculated using the formula in Eq. 1.

$$\text{E}\dot{\text{D}}\left(\frac{\text{Gy}}{\text{s}}\right) = \left(\text{CBE}_\text{B} \times \dot{\text{D}}_\text{B}\right) + \left(\text{RBE}_\text{N} \times \dot{\text{D}}_\text{N}\right) + \left(\text{RBE}_\text{H} \times \dot{\text{D}}_\text{H}\right) + \left(\text{W}_\gamma \times \dot{\text{D}}_\gamma\right) \quad (1)$$

the with $\dot{D}_B$ is alpha dose, $\dot{D}_N$ is neutron dose, $\dot{D}_H$ is proton dose, and $\dot{D}_\gamma$ is gamma dose [32], [33]. The CBE and RBE values used are in Table 2 [34].

Table 2. Table of CBE and RBE values

Tissue Type	CBE	RBE$_N$	RBE$_H$	RBE$_\gamma$
Tumour	3.8	2.9	2.4	1
Skin	2.5	2.9	2.4	1
Bone	1	2.9	2.4	1
Soft Tissue	1.34	2.9	2.4	1

b. Irradiation Time

To kill cancer cells, BNCT requires an estimated therapy time. The irradiation time (t) needed to achieve the minimum dose value for the GTV can be determined. For breast cancer, the minimum dose required to kill cancer cells is 30 Gy [35, 36]. Irradiation time can be calculated using Eq. 2 [37].

$$\text{irradiation time (s)} = \frac{\text{minimum dose(Gy)}}{\dot{\text{D}}_{\text{total}}\left(\frac{\text{Gy}}{\text{s}}\right)} \quad (2)$$

The total dose is the total dose rate for cancer cells.

c. Equivalent Dose

After the exposure time, the equivalent dose can be calculated from healthy and cancer tissue. The equivalent dose is used to determine the damage that occurs to healthy tissue around the tumor. The absorbed dose for each organ can be calculated using Eq. 3 [37].

$$\text{D}_{\text{eq}}\,\text{OAR (Gy)} = \left(\text{E}\dot{\text{D}}\,\text{OAR}\,\frac{\text{Gy}}{\text{s}}\right) \text{x irradiation time (s)} \quad (3)$$

Dose distribution and exposure time in BNCT were carried out using PHITS and calculated for each variation of Boron concentration used,

namely 30 µg/g, 60 µg/g, 90 µg/g, 120 µg/g, and 150 µg/g. This takes into account previous research by Ardana. In his study, the Boron concentration varied from 20 to 40 µg/g of tissue, and the results obtained were that concentrations below 30 µg/g caused damage to the skin because the dose received exceeded the threshold limit. Meanwhile, the resulting exposure time at concentrations of 35 µg/g and 40 µg/g is less than 30 minutes [31].

3. RESULTS AND DISCUSSION

3.1 Irradiation Geometry

There are two comparisons between neutron irradiation at LLAT (left lateral) and AP (anterior-posterior) to determine the most effective radiation position in breast cancer treatment. Lighting direction LLAT is the direction of radiation from the left side of the patient's body. It targets the area affected by cancer from the left side. Meanwhile, the AP radiation direction is from the front to the back of the patient's body. It targets the area affected by cancer directly from the front. Figures 6 and 7 show the design direction of the BSA collimator with the ORNL phantom from the AP and LLAT irradiation directions, illustrating the differences in irradiation approaches and how each direction can influence the radiation dose distribution in cancer tissue.

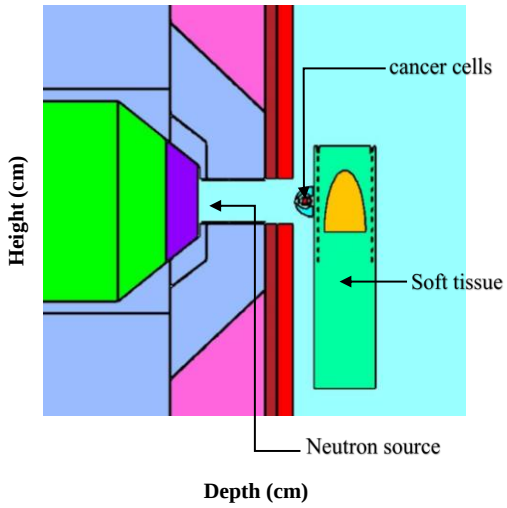

Fig. 6. Visualization of AP radiation in the sagittal section

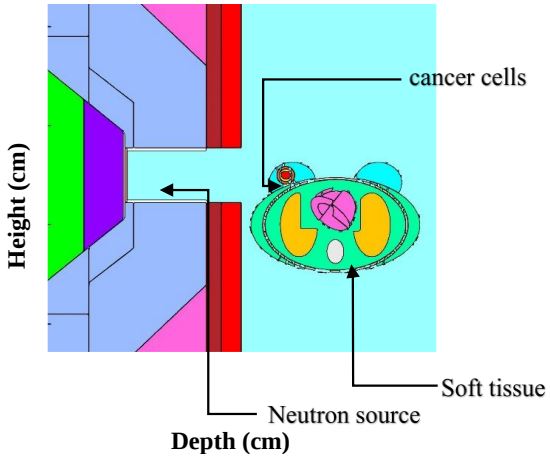

Fig. 7. Visualization of LLAT radiation in the axial section

Based on the geometric results obtained from the PHITS program *output*, there are differences in the irradiation distance between the LLAT and AP irradiation directions to cancer tissue. In LLAT irradiation, the distance between the neutron source and the target tissue (GTV) is 8.8 cm, while in AP irradiation, the distance is only 2 cm. Therefore, radiation from the AP direction is more effective because the distance between the cancer tissue and the neutron source is closer, so more neutron flux reaches the cancer tissue. In addition, radiation from the AP direction directly targets cancer tissue, causing the surrounding tissue (OARs) to receive a much lower dose than radiation from the LLAT direction.

3.2 Neutron Flux

Neutron energy ranges are classified into thermal, epithermal, and fast neutrons. Thermal neutrons have an energy of approximately 0.025 eV, epithermal neutrons range from 0.025 eV to 0.5 MeV, and fast neutrons have energies greater than 0.5 MeV. During the moderation stage, neutrons are redistributed according to their energy levels. As epithermal neutrons enter the body, their flux decreases due to their transformation into thermal neutrons during collisions with atomic nuclei in the tissue, a process known as thermalization. The deeper the epithermal neutron flux penetrates into the phantom, the faster the thermalization process occurs, leading to a reduction in the neutron flux value [17].

The characteristic value of the neutron flux for each tissue is calculated based on the depth within the phantom, starting from 0 cm at the irradiation point. Figure 8 shows a graph of the neutron flux results in the phantom in the AP illumination direction, while the LLAT direction has similar flux values and characteristics.

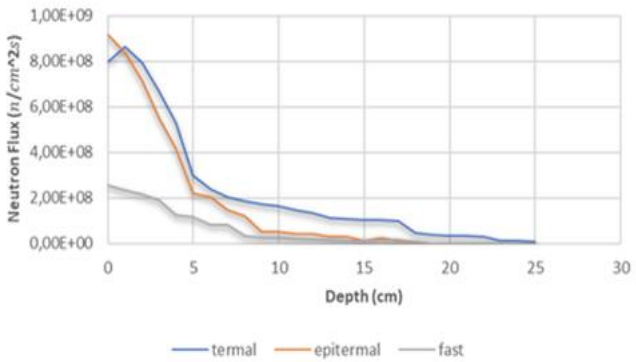

Fig. 8. Graph of Neutron Flux per Depth

Neutron flux distribution describes how neutrons are dispersed in a medium or target. Figure 8 shows that the phantom's maximum depth of thermal neutron flux is 17 cm, while epithermal neutrons have a maximum depth of 9 cm. The maximum thermal flux value is at a depth of 1 cm, corresponding to the location of cancer tissue. This is because a greater concentration of B-10 is deposited in cancer tissue. Then, the thermal flux value will decrease, caused by hydrogen and nitrogen atoms absorption interaction in the tissue. Like thermal neutron flux, epithermal neutron flux will also experience a decrease in the flux value due to scattering interactions with the components that make up the tissue.

3.3 Equivalent Dose Rate

The neutron flux value obtained in each organ will influence the dose rate value received by the body tissue. Figure 9 shows the distribution of Boron, neutron, proton, and gamma dose rates in AP irradiation, and Fig. 10 shows the distribution of Boron, neutron, proton, and gamma dose rates in LLAT irradiation with a concentration of 150 µg/g.

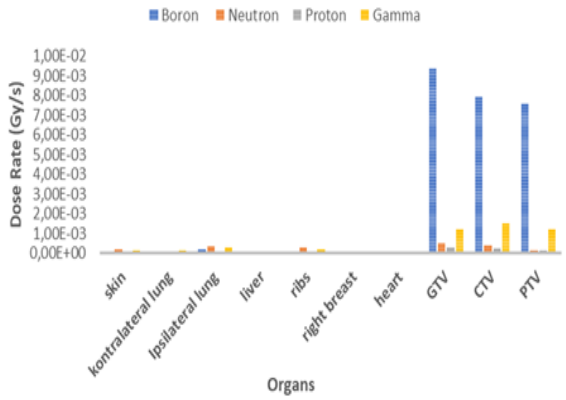

Fig. 9. Boron, Proton, Gamma, and Neutron dose rates in several parts of the breast under AP irradiation

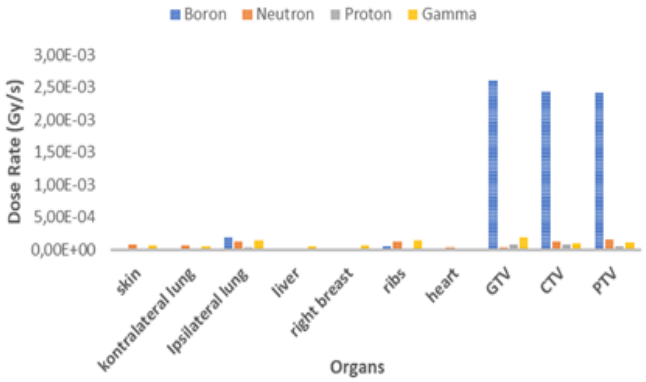

Fig. 10. Boron, proton, gamma, and neutron dose rates in several parts of the breast under LLAT irradiation

The research showed that the Boron dose rate had higher results than others. In both the AP and LLAT irradiation directions, the Boron dose rate value is deposited in the cancer tissue (GTV). The dose rate value will also influence the cancer tissue's total dose rate value. Figures 11 and 12 show that the total dose rate values in the OAR have different values in the AP and LLAT radiation directions.

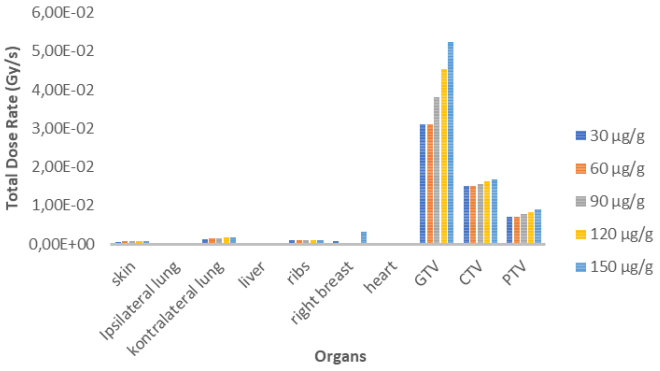

Fig. 11. Total OARs Dose Rate in AP direction

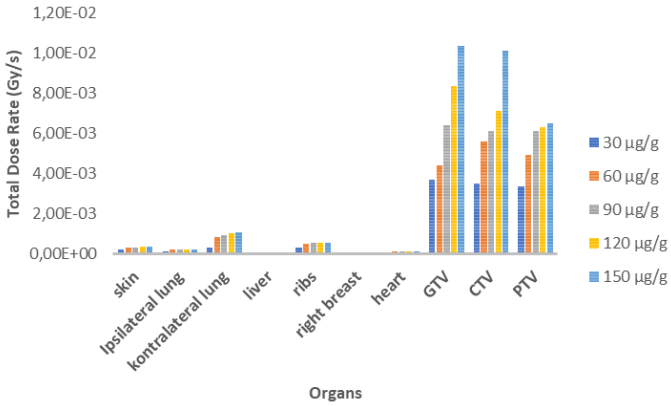

Fig. 12. Total OARs Dose Rate in LLAT direction

The ratio of Boron concentrations between cancer and healthy tissue is 10:1. Healthy tissue will only receive 0.3% of the entire Boron concentration injected into the body [24], so cancer tissue will

receive a higher dose than healthy tissue. The total dose rate will increase as the Boron concentration rises, as shown in Fig. 13.

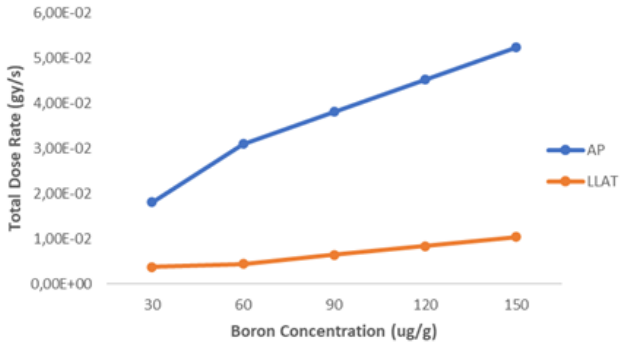

Fig. 13. Effect of Boron concentration on total dose rate

Figure 13 compares the total dose rate (Gy/s) between AP and LLAT irradiation techniques at various Boron concentrations (µg/g). The graph shows that both irradiation techniques will increase the total dose rate and boron concentration. However, the AP technique consistently shows higher dose rate results than the LLAT technique. This indicates that the AP technique delivers the radiation dose to the target more efficiently than the LLAT technique.

3.4 Time Irradiation

The total dose rate obtained will determine the irradiation time needed to kill cancer cells. Figure 14 shows the correlation between B-10 concentration and irradiation time. The greater the amount of injected boron, the shorter the resulting irradiation time will be.

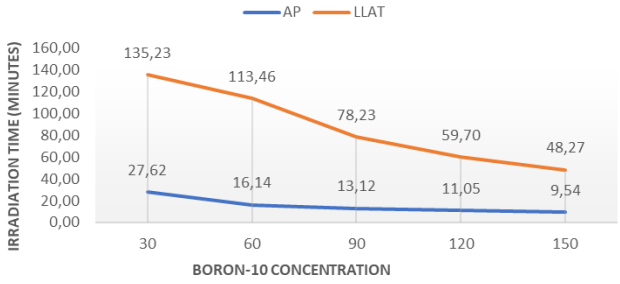

Fig. 14. LLAT Irradiation Time Graph

Figure 14 shows a graph of the exposure time in the AP and LLAT directions required for each Boron concentration in cancer tissue. From the results in Figure 14, it can be seen that the AP irradiation method shows a relatively constant irradiation time with a slight decrease as the Boron concentration increases, namely from 27.62 minutes at a concentration of 30 µg/g to 9.54 minutes at a concentration of 150 µg/g. In contrast, the LLAT directional irradiation method shows a more significant decrease in irradiation time when the Boron concentration increases, from 150.12 minutes at 30 µg/g to 48.27 minutes at a maximum 150 µg/g concentration. This shows that the AP radiation method tends to have more stable effectiveness than the LLAT radiation method. Thus, the AP irradiation method can provide consistent irradiation times at various B-10 concentration levels. In addition, Fig. 14 shows that the irradiation time produced using a boron concentration of 150 µg/g tissue is effective for breast cancer treatment because it is less than one hour [31].

3.5 Equivalent Dose

It is known that high concentrations of boron increase the interaction between neutrons and boron, which can affect the production of alpha particles that kill cancer cells.

One of the tissues affected by radiation is the skin. Radiation-induced skin injury can manifest within days to weeks after exposure, with rapid reactions like erythema appearing within hours to 24 hours after exposure to doses greater than 2 Gy. Acute radiation injuries, including erythema, erosion, temporary hair loss, vesicles, pain, and itching, can last up to 9 weeks [38]. Considering the increased risk, the maximum safe dose to the skin is 2 Gy [38],[39]. Like the skin, the dose to other healthy tissues must also be carefully managed to minimize radiation damage while effectively targeting cancerous tissue. As with the skin, the dose to other healthy tissue must also be considered to minimize damage to healthy tissue due to radiation exposure to kill cancerous tissue. For the lungs, the maximum dose is 5 Gy; exceeding this dose may lead to pneumonia [33, 39]. For the ribs, exceeding a dose limit of 30 Gy can cause bone toxicity [40]. Radiation-induced heart disease can manifest as coronary artery disease, pericardial disease, ischemic heart disease, valve disease, and arrhythmia [41]. Therefore, the maximum recommended dose for the entire heart is 2 Gy [42].

The dose received by an organ can be calculated by multiplying the total dose rate by the irradiation time. Among the two irradiation directions, a boron concentration of 150 µg/g resulted in the shortest irradiation times: 9.54 minutes for the AP direction and 48.27 minutes for the LLAT direction. Table 5 shows data on the dose received by cancer and healthy tissue and the dose limits received.

Table 5. OARs dose, direction of irradiation, and irradiation time

OAR	**Irradiation Technique**	AP	LLAT
	Irradiation Time	9.54 min	48.27 min
	Dose Tolerance (Gy)	**Equivalent Dose (Gy)**	
Skin	2.00	0.46	1.03
Ipsilateral lung	5.00	1.01	2.19
Contralateral lung	2.7	0.16	0.72
Ribs	30.00	0.61	1.62
heart	2.00	0.11	0.40

The table compares the radiation dose absorbed by several OARs during AP and LLAT irradiation techniques with irradiation times of 9.54 minutes and 48.27 minutes, respectively. These data include each organ's dose tolerance (Gy) and absorbed dose (Gy) during both irradiation techniques. The AP technique has a shorter irradiation time and generally produces a lower absorbed dose to the organs at risk than the LLAT technique. In the ipsilateral lung, the dose absorbed with LLAT (2.19 Gy) was close to the dose tolerance limit (5.00 Gy), while LAT remained below the tolerance limit (1.01 Gy). In the contralateral lung, the absorbed dose with both techniques (0.16 Gy for AP and 0.72 Gy for LLAT) was well below tolerance (2.7 Gy).

The LLAT technique approached the dose tolerance limit to skin (1.03 Gy against a tolerance of 2.00 Gy), while AP was well below the tolerance limit (0.46 Gy). Both techniques remained well below the dose tolerance limits for the heart (0.11 Gy for AP and 0.40 Gy for LLAT out of tolerance 2.00 Gy). For the ribs, both techniques also remained well below tolerance limits (0.61 Gy for AP and 1.62 Gy for LLAT out of a tolerance of 30.00 Gy). Thus, the AP technique is safer in keeping the dose absorbed by critical organs below the recommended tolerance limits.

To validate the data in this study, a BNCT study for breast cancer was used as a reference for comparison, as shown in Table 6. The accelerator-based BNCT clinical study focuses on three cases of recurrent breast cancer after radiation therapy to assess the effects on the thoracic region, particularly the risk of radiation pneumonitis. This single-center, open-label study was conducted by Stella Pharma Corporation (Osaka, Japan) [33].

Table 6. BNCT studies results

Study	Tumor Dose (Gy)	Ipsilateral lung (Gy)	Result
In a 72-year-old woman (T2N1M0), recurrence occurred in the left parasternal lymph nodes, which were treated with 59 Gy of irradiation delivered in 30 fractions	31.4	5	After 30 and 90 days, CT scans were performed and showed no evidence of radiation pneumonitis
In a 61-year-old woman (T2N1M0), recurrence occurred in the left chest after irradiation with 50.4 Gy delivered in 28 fractions	23.6	2.7	CT scans performed on days 1, 7, 30, 60, and 90 following BNCT revealed no signs of radiation pneumonitis
In a 52-year-old woman (T3N2M0), Local recurrence occurred in the right breast, which was irradiated with 50 Gy delivered in 25 fractions	30	3.7	CT scans performed on days 1, 7, 30, 60, and 90 following BNCT revealed no signs of radiation pneumonitis

The case studies in Table 6 were compared to patients who had undergone conventional radiotherapy before BNCT treatment. BNCT's advantage is that it can deliver a lower dose than conventional therapy in a single fraction while ensuring a safe dose for the surrounding healthy tissue. In the three cases, the average dose to the ipsilateral lung was 5 Gy-Eq, and there were no instances of radiation pneumonitis within 90 days [33].

4. CONCLUSION

Simulation results of breast cancer therapy with BNCT using PHITS version 3.34 show that the AP irradiation technique is more effective and efficient in delivering radiation doses to cancer tissue than the

LLAT method. In the AP method, the total dose rate is higher and remains stable with increasing boron concentration, resulting in shorter and more consistent irradiation times. Thus, the AP method can provide an optimal radiation dose to cancer tissue with a more efficient irradiation time.

The AP method is considered safer than the LLAT method because it results in a lower dose to critical organs. The dose received by healthy organs remains below the tolerance threshold, minimizing the risk of damage to healthy tissue. Therefore, the AP irradiation method is recommended for breast cancer treatment using BNCT, as it offers an optimal balance of treatment effectiveness and patient safety. However, before this method can be widely implemented, it must first receive approval from BAPETEN, ensuring that all technical and administrative aspects are thoroughly validated.

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