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Determination of Neutron Flux in Brain Cancer Boron Neutron Capture Therapy Using Monte Carlo Simulation

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Abstract

Boron Neutron Capture Therapy (BNCT) is a relatively safer technology for killing cancer cells, one of which is the Glioblastoma multiforme. One of the main components of the BNCT equipment is the collimator which functions as an exit point for epithermal neutron particles that hit cancer cells. In addition to the experimental method, BNCT research can be carried out by modeling, including using the MCNPX software based on the Monte Carlo Method. This research aimed to determine the flux distribution of fast and epithermal neutrons and the dose rate of fast neutrons and gamma that hit the target cancer cells in the phantom head of ORNL MIRD. Modeling using the MCNPX software has three main parts: cell cards, surface cards, and data cards. A tally is used on the data card to calculate the neutron flux. Based on the calculation of the modeling results, the flux of epithermal neutron is 2.87 x 109 n/cm2.s. The dose ratio of the epithermal to the fast neutron flux is 2.29 x 10-14 Gy.cm2/n. Then, the balance of the dose rate of the epithermal to the gamma is 1.64 x 10-14 Gy.cm2/n, and the ratio of epithermal to thermal neutron flux is 0.004. In this study, the epithermal neutron flux hitting the target cancer cells in cell target was moderated at 4 cm so that at a depth of 8 cm, the energy was converted into thermal neutrons. Based on the analysis of the results, it can be concluded that the neutron flux that will interact with cancer tissue is thermal neutrons, not epithermal neutron flux.

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INTRODUCTION

Glioma brain cancer is the most common, with an incidence rate of up to 51% compared to other primary brain cancers (Hasan & Sekarutami, 2014). Glioma has several types, one of which is glioblastoma multiforme. Glioblastoma multiforme is a type of primary tumor in the brain that originates from glial cells and is a central nervous system tumor classified as High-grade glioma (HGG) grade IV. At this grade, brain cancer is challenging to treat because the tumor overgrows, is malignant, and can spread to the surrounding healthy tissue (Raharjo & Supriana, 2018). Current brain cancer treatment methods include radiotherapy, chemotherapy, and surgery. In treating glioblastoma multiforme patients, safer and more effective therapies have been developed. BNCT is a cancer-healing technique that utilizes thermal neutron capture by the Boron nucleus (^{10}B) (Dea & Novitasari, 2016). Until now, two Boron compounds have been used for BNCT, Sodium Boroncaptate (BSH) and Boronphenylalanine (BPA). BSH accumulates around the cell membrane, while BPA accumulates in the cell nucleus (Nurwati & Prasetya, 2014). BNCT treatment is carried out by injecting a ^{10}B carrier agent into cancer cells and irradiating a beam of neutrons. This reaction produces α particles and ^{7}Li nuclei, and these α particles serve as target cancer cell killers (Ramadhani, et al., 2020). The range of α and Li particles ranges from (8-10) μm to (4.5-5) μm so that the deposited energy is limited only in the size of the cell diameter, which is ±18 μm (Nedunchezhian, et al., 2016).

Neutron sources that play a role in BNCT therapy are nuclear reactors, Compact Neutron Generator (CNG), accelerators, and radionuclides. In this study, the source used is derived from a nuclear reactor. Nuclear reactors produce a wide spectrum of neutrons, from fast neutrons to thermal neutrons. In BNCT therapy, the neutron used must be in the thermal or epithermal neutron range. Neutrons originating from this reactor do not meet the requirements to be applied directly to BNCT because the resulting neutrons are still fast. A collimator is needed to change the characteristics of the neutrons produced by the reactor. The collimator changes the characteristics of fast neutrons into epithermal neutrons used in BNCT therapy.

One of the research methods regarding BNCT is modeling using software based on the Carlo Method. Several research topics related to BNCT modeling have been developed, including calculating photon doses in brain cancer therapy (Dea & Novitasari, 2016). In addition, modeling related to shielding has also been carried out on BNCT (Sardjono, 2019). One Monte Carlo Method-based software commonly used in BNCT modeling is Monte Carlo N-Particle eXtended (MCNPX). Monte Carlo N-Particle eXtended (MCNPX) is a software method based on the Monte Carlo method used to simulate particle traces of neutrons, photons, or electrons (Brown, 2003). Neutron particle simulation in MCNPX is carried out by taking random statistical samples. The probability of this random distribution uses particle transport data to determine each stage of particle interaction (Muslih, et al., 2014; Sardjono, 2019). This program simulates the journey of a neutron's life from birth until the body absorbs it. In this research, we analyzed the output of neutrons from the collimator and the value of the neutron flux absorbed by the target. The method used is the Monte Carlo method with the MCNPX program.

METHODS

In this study, modeling was carried out using the MCNPX software. The software simulates activity and calculates the flux of neutrons in healthy tissue around cancer. Modeling is done by making a collimator, head phantom, and cancer geometry. The neutron comes from the collimator modeling of the Kartini Research Reactor, which is operated with a power of 100 kW (Fauziah, et al., 2013). The body organs were modeled using the ORNL-MIRD phantom head and neck (Lazarine, 2006). Reactor output data in the form of neutron flux in Ring B of 1.24×10^{12} n.cm^2.s-1 will be used as collimator data input (Fauziah, et al., 2013). The collimator consists of a collimator wall made of nickel material with a thickness of 5 cm, reflecting the neutrons and stabilizing the energy of the neutrons. The moderator is aluminum material with a thickness of 60 cm, which reduces the power of fast neutrons, so the value is equivalent to thermal neutrons. In this BNCT modeling, the filter used is made of nickel at a thickness of 15 cm, which functions to filter out fast neutrons and thermal neutrons, but frees epithermal neutrons. The next component is gamma shielding, made of Bismuth with a thickness of 2 cm and acts as a barrier to gamma radiation. The neutron barrier is made of $^{6}LiCO_3$-polyethylene with a thickness of 3 cm, which functions to absorb more neutrons than they scatter. The equipment arrangement is presented in Figure 1.

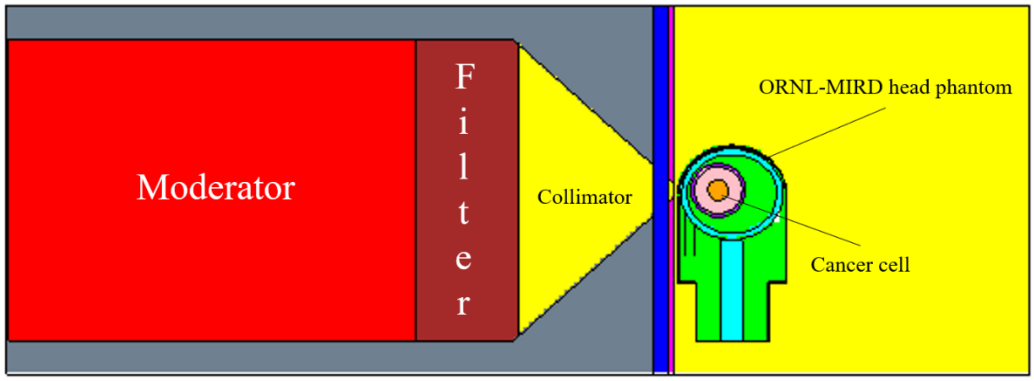

Figure 1. Collimator Design and Phantom

The method used in the collimator consists of spectrum shifting and filtering. Both ways are commonly used in BNCT technology. In the spectrum shifting method, the moderator used functions to decrease the energy of fast neutrons to the energy range of epithermal neutrons. In contrast, filtering uses materials that can absorb thermal and fast neutron energy but free epithermal neutrons. This research requires test parameters to determine the purity level of the epithermal beam passed from the collimator. The parameters used to test the value of epithermal neutron flux are thermal neutron flux (ϕ_{th}/ϕ_{epi}), gamma dose rate ($\dot{D}_f/\phi_{epi}$), and fast neutron dose rate ($\dot{D}_\gamma/\phi_{epi}$). Neutron sources simulated in the MCNPX program are divided into three energy ranges: thermal neutrons with energy $\leq$ 5x10^{-7} MeV, epithermal neutrons $\leq$ 0.01 MeV, and fast neutrons with energy $\leq$ 20 MeV. The tally used in this study is the tally F:4 to calculate the average flux that passes through a cell, Tally F:34 to calculate the absorbed dose rate of neutrons, and Tally F:24 to calculate the rate of absorbed dose of gamma (Pelowitz, 2008). In this study, normalization is also needed because the calculation results from the MCNPX modeling software in the form of tally data units on the volume geometry do not match the units set by the IAEA. The normalization required to convert the 100 kW power used in the reactor into a fission rate satisfies the equation (1):

$$(10^5\text{W})\left(\frac{1J/s}{W}\right)\left(\frac{1\ MeV}{1.602\ x\ 10^{-13}j}\right)\left(\frac{1\ fisi}{200\ MeV}\right) = \text{fission rate } (fisi/s) \quad (1)$$

The fission rate of 3.121 x 10^{15} fission/s is then used to normalize the tally of the neutron beam. The normalization factor for neutrons is calculated using equation (2):

$$(3.121\ \text{x}\ 10^{15}\ fisi/s)(2.42\ neutron/fisi) = \text{neutron rate } (neutron/s) \quad (2)$$

Because the neutron output from the Kartini Reactor is in the form of continuous neutrons, an energy dose (de) is needed for the energy value and a dose function (df) to convert the energy value into an amount. The results of the tally calculation in the MCNPX modeling are the dose rate of neutrons and gamma rays and the value of the neutron flux (n.cm^{-2}.s^{-1}) and (Gy/s).

RESULTS AND DISCUSSION

After MCNPX modeling, several research parameters were obtained. These parameters are fast, epithermal, and thermal neutron flux. Other parameters resulting from this study are the value of the gamma dose rate and the neutron dose rate. The details of several parameters, along with their values and units from the collimator output are presented in Table 1.

Table 1. Collimator Output

Parameter	Output	Unit
Thermal neutron flux	1.26 x 10^7	n.cm^{-2}.s^{-1}
Fast neutron flux	5.05 x 10^7	n.cm^{-2}.s^{-1}
Epithermal neutron flux	2.87 x 10^9	n.cm^{-2}.s^{-1}
Fast neutron dose rate	6.59 x 10^{-5}	Gy/s
Gamma dose rate (primary)	4.74 x 10^{-5}	Gy/s

Table 1 shows that epithermal neutrons, fast neutrons, and thermal neutrons dominate the collimator output. In addition to the three types of flux, the BNCT process also considers the gamma and fast neutron. The fast neutron is greater than the gamma. This is because the quantity of neutrons

formed is greater than the resulting gamma. Even so, the difference in the values of the two parameters is relatively small. Then, to determine the output quality of the collimator, namely the epithermal, the ratio of the gamma to the epithermal, the ratio of the fast neutron to the epithermal neutron flux, and the ratio of thermal neutron flux to epithermal neutron flux, the International Atomic Energy Agency (IAEA) using multiple test parameters. According to the standard, the recommended epithermal flux value in the BNCT therapy process is more than >1.0 x 10^9 n.cm^{-2}.s^{-1}. In this study, the value of the epithermal neutron flux generated from the collimator was 2.87 x 10^9 n.cm^{-2}.s^{-1}. This value exceeds the recommended one based on a comparison with IAEA standards. The epithermal neutron flux affects the length of irradiation time. The greater the epithermal flux value, the faster the irradiation time.

The next aspect is calculating the ratio of the fast neutron to the epithermal neutron ($\dot{D}_f/\phi_{epi}$). The test value is used to determine the optimization of the moderator used. Based on the calculation results, the neutron flux originating from the reactor is in the fast neutron energy range. Therefore, a moderator is needed to hold the neutrons in the epithermal neutron energy range. The moderator used in the BNCT process must be able to reduce the ratio between the fast neutron dose rate and the epithermal neutron flux. In this study, it was found that the ratio of the value of the fast neutron dose rate to the epithermal neutron flux was 2.29 x 10^{-14} Gy.cm^2/n. The following test parameter is the percentage of the value of the gamma to the epithermal ($\dot{D}_\gamma/\phi_{epi}$). The test is used to determine the optimization of the gamma shielding used. In BNCT activity, the gamma radiation shielding material reduces the intensity of the emitted gamma without significantly decreasing the epithermal. After calculating the modeling results, the value of gamma to epithermal neutron in this study is 1.64 x 10^{-14} Gy.cm^2.n^{-1}. The following parameter is the value of the ratio of thermal neutron to epithermal neutron (ϕ_{th}/ϕ_{epi}). These test parameters play a role in determining the optimization of the filter material used in the collimator. In this study, the filter used has the task of reducing the value of the thermal neutron flux. However, the filter can release epithermal neutron flux, so the test parameter for the filter is thermal neutron flux. After doing the calculations, it was found that the value of the ratio between the thermal neutron flux and the epithermal neutron flux was 0.004. The calculation results for several parameters from the collimator in this study are shown in Table 2.

Table 2. Calculation Results of the Collimator Output Parameters

Parameter	Notations	Unit	Collimator Output
Epithermal neutron flux	ϕ_{epi}	$\left(\frac{n}{cm^2.s}\right)$	2.87 x 10^9
Comparison of fast to epithermal neutron	$\frac{\dot{D}_f}{\phi epi}$	$\left(\frac{Gy.cm^2}{n}\right)$	2.29 x 10^{-14}
Comparison of the value of the gamma to the epithermal	$\frac{\dot{D}\gamma}{\phi epi}$	$\left(\frac{Gy.cm^2}{n}\right)$	1.64 x 10^{-14}
Percentage of the thermal neutron value to the epithermal	$\frac{\phi_{th}}{\phi_{epi}}$	-	0.004

In the case of brain cancer BNCT modeling, the phantom used is the ORNL-MIRD phantom. The neutrons fired at the target cancer cells are heterogeneous because they consist of epithermal, fast, and thermal neutrons. Therefore, calculating the flux value of each type of neutron hitting the target organ is carried out. In this study, the flux value of each neutron is presented as a graph of the flux distribution to the depth of the target organ, according to Figure 2.

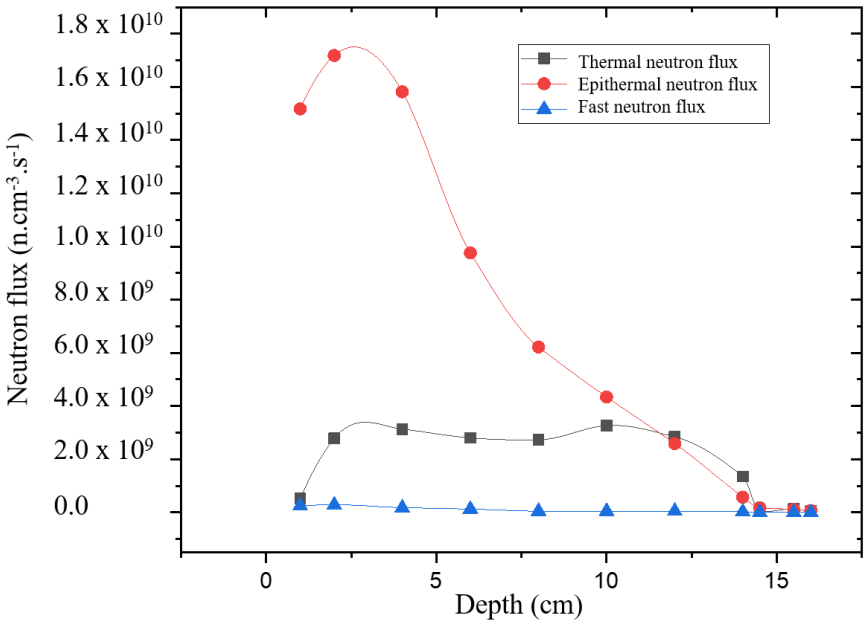

Figure 2. Graph of flux distribution at head phantom depth

Based on the graph in Figure 2, it can be analyzed that when the neutrons penetrate the patient's body tissue, the thermal neutron flux value is stable. However, the epithermal neutron flux value decreased. Based on the calculation results, the thermal neutron flux in body tissues tends to be durable and reaches a peak at 10 cm, namely 3.27 x 10^9 n.cm^{-3}.s^{-1}. The fast neutron has a reasonably low weight, which tends to be close to zero. Then, the value of the epithermal neutron flux increased and reached a peak of 1.72E+10 n.cm^{-3}.s^{-1} at a depth of 2 cm. However, the value of the epithermal neutron flux decreased significantly at a depth of 4 cm. The decrease in the value of the epithermal neutron flux occurs because the epithermal neutron flux experiences moderation. Moderation is an event of a reduction in the energy of a neutron because it interacts with materials in the body. The decrease in the power of epithermal neutrons up to the energy range of thermal neutrons is presented in Figure 3.

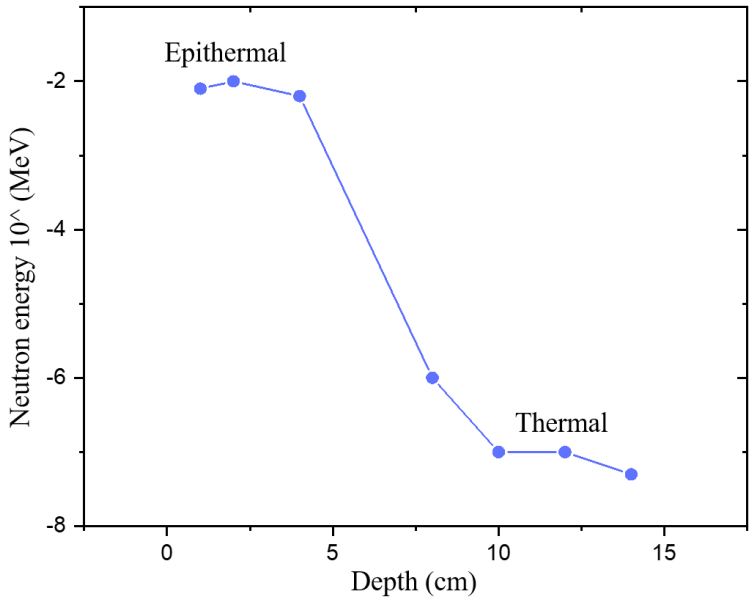

Figure 3. Graph of neutron energy to phantom depth

Figure 3 shows the energy change of the neutron when it penetrates the target organ of the BNCT. At the beginning of penetration, the incoming neutrons have the energy range of epithermal neutrons. However, at a depth of 4 cm, the energy of these neutrons decreases significantly. Finally, at a depth of 8 cm to 14 cm, the power of the epithermal neutrons changes to a range of

thermal neutron energies. These results follow IAEA provisions that epithermal neutrons can penetrate tissue between 8 to 10 cm and maximum thermal neutrons at a depth of 2 to 3 cm (IAEA, 2001). The significant decrease in the significance of the epithermal neutrons significantly affects the thermal neutrons as they penetrate the network. Epithermal neutrons irradiated into the body will turn into thermal neutrons at a certain depth so that the neutron flux that will interact with Boron-10 (^{10}B) in cancer tissue is thermal neutrons, not epithermal neutrons (Ardana, et al., 2019).

CONCLUSION

From the study's results, it can be concluded that the collimator neutron's flux of epithermal neutron is 2.87 x 10^9 n/cm^2.s. The dose ratio of the epithermal to the fast neutron flux is 2.29 x 10^{-14} Gy.cm^2/n. Then, the balance of the dose rate of the epithermal to the gamma is 1.64 x 10^{-14} Gy.cm^2/n, and the ratio of epithermal to thermal neutron flux is 0.004. In addition, epithermal neutrons irradiated into the body moderate at a depth of 4 cm, and reach thermal neutron energy at a depth of 8 cm, so that the neutron flux that will interact with cancer tissue is thermal neutrons, not epithermal neutron flux.

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