

OPTIMIZATION OF A NEUTRON BEAM SHAPING ASSEMBLY DESIGN FOR BNCT AND ITS DOSIMETRY SIMULATION BASED ON MCNPX

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ABSTRACT

OPTIMIZATION OF A NEUTRON BEAM SHAPING ASSEMBLY DESIGN FOR BNCT AND ITS DOSIMETRY SIMULATION BASED ON MCNPX. This article involves two main objectives of BNCT system. The first goal includes optimization of 30 MeV Cyclotron-based Boron Neutron Capture Therapy (BNCT) beam shaping assembly. The second goal is to calculate the neutron flux and dosimetry system of BNCT in the head and neck soft tissue sarcoma. A series of simulations has been carried out using a Monte Carlo N Particle X program to find out the final composition and configuration of a beam shaping assembly design to moderate the fast neutron flux, which is generated from the thick beryllium target. The final configuration of the beam shaping assembly design includes a 39 cm aluminum moderator, 8.2 cm of lithium fluoride as a fast neutron filter and a 0.5 cm boron carbide as a thermal neutron filter. Bismuth, lead fluoride, and lead were chosen as the aperture, reflector, and gamma shielding, respectively. Epithermal neutron fluxes in the suggested design were 2.83×10^9 n/s cm⁻², while other IAEA parameters for BNCT beam shaping assembly design have been satisfied. In the next step, its dosimetry for head and neck soft tissue sarcoma is simulated by varying the concentration of boron compounds in ORNL neck phantom model to obtain the optimal dosimetry results. MCNPX calculation showed that the optimal depth for thermal neutrons was 4.8 cm in tissue phantom with the maximum dose rate found in the GTV on each boron concentration variation. The irradiation time needed for this therapy were less than an hour for each level of boron concentration.

Keywords: Optimization, Beam Shaping Assembly, BNCT, Dosimetry, 30 MeV Cyclotron, MCNPX.

ABSTRAK

OPTIMASI DESAIN KOLIMATOR NEUTRON UNTUK SISTEM BNCT DAN UJI DOSIMETRINYA MENGGUNAKAN PROGRAM MCNPX. Telah dilakukan penelitian tentang sistem BNCT yang meliputi dua tahapan simulasi dengan menggunakan program MCNPX yaitu uji simulasi untuk optimasi desain kolimator neutron untuk sistem BNCT berbasis Siklotron 30 MeV dan uji simulasi untuk menghitung fluks neutron dan dosimetri radiasi pada kanker sarkoma jaringan lunak pada leher dan kepala. Tujuan simulasi untuk mendapatkan desain kolimator yang paling optimal dalam memoderasi fluks neutron cepat yang dihasilkan dari sistem target berilium sehingga dapat dihasilkan fluks neutron yang sesuai untuk sistem BNCT. Uji optimasi dilakukan dengan cara memvariasikan bahan dan ketebalan masing-masing komponen dalam kolimator seperti reflektor, moderator, filter neutron cepat, filter neutron thermal, filter radiasi gamma dan lubang keluaran. Desain kolimator yang diperoleh dari hasil optimasi tersusun atas moderator berbahan Al dengan ketebalan 39 cm, filter neutron cepat berbahan LiF₂ setebal 8,2 cm, dan filter neutron thermal berbahan B₄C setebal 0,5 cm. Untuk reflektor, filter radiasi gamma dan lubang keluaran masing-masing menggunakan bahan PbF₂, Pb dan Bi. Fluks neutron epithermal yang dihasilkan dari kolimator yang didesain adalah sebesar $2,83 \times 10^9$ n/s cm⁻² dan telah memenuhi seluruh parameter fluks neutron yang sesuai untuk sistem BNCT. Selanjutnya uji simulasi dosimetri pada kanker sarkoma jaringan lunak pada leher dan kepala dilakukan dengan cara memvariasikan konsentrasi senyawa boron pada model phantom leher manusia (ORNL). Selanjutnya model phantom tersebut diiradiasi dengan fluks neutron yang berasal dari kolimator yang telah didesain sebelumnya. Hasilnya, fluks neutron thermal mencapai nilai tertinggi pada kedalaman 4,8 cm di dalam model phantom leher ORNL dengan laju dosis tertinggi terletak pada area jaringan kanker. Untuk masing-masing variasi konsentrasi senyawa boron pada model phantom leher ORNL supaya dapat mematikan jaringan kanker, membutuhkan waktu iradiasi neutron kurang dari satu jam.

Kata kunci: Optimasi, Kolimator, BNCT, Dosimetri, Siklotron 30 MeV, MCNPX

INTRODUCTION

Cancer begins when cells in a part of the body start to grow out of control. There are many kinds of cancer, but they all start due to the uncontrolled growth of abnormal cells. One type of cancer that can affect the human body is a soft tissue sarcoma. Soft-tissue sarcoma is rare, with an annual incidence around 5 per 100,000 [1]. Malignant fibrous histiocytoma, fibrosarcoma, angiosarcoma and malignant peripheral nerve sheath tumor are the most frequently found sarcoma types in the head and neck [2]. Soft tissue sarcomas account for the majority (80%) of all sarcomas in the human body and constitute about 20% of all sarcomas affecting the head and neck regions in adults and approximately 35% in children. The face and neck are the most frequent sites affected in the head and neck region as shown in Figure 1 [3].



Figure 1. Clinical photographs of patients with soft tissue sarcoma [3]

A wide variety of therapeutic approaches is used in the management of these cancers. Traditionally, surgery has been considered to be the treatment of choice. Due to the high rate of recurrence of these tumors after surgery, radiotherapy and chemotherapy have recently been added as additional treatment strategies to improve disease control and prognosis [4]. Radiation therapy is followed after resection of all high-grade sarcomas and large tumors, and when margins of resection are closed or microscopically involved. Systemic chemotherapy is recommended for tumors with a significant risk of distant metastases [5]. However, cancer treatment with radiation and chemotherapy methods are also able to trigger other cancers in the body [1]. It is important to develop a new cancer therapy method that can be used to overcome some of the weaknesses of previous cancer therapy methods. Currently, a therapy has been developed that is expected to deal with soft tissue sarcoma. That cancer treatment method is known as Boron Neutron Capture Therapy (BNCT) [6].

Boron Neutron Capture Therapy (BNCT) has for many decades been advocated as an innovative form of radiotherapy that, in principle, has the potential to be the ideal form of treatment for many types of cancers [7]. BNCT is a particular kind of tumor treatment based on the possibility of selectively accumulating the isotope ^{10}B in tumor tissue as shown in Figure 2 [8]. BNCT is a binary treatment modality that involves the selective accumulation of boron carriers in tumors followed by irradiation with a thermal or epithermal neutron beam. The high linear energy transfer (LET) α particles and recoiling ^7Li nuclei are emitted during the capture of thermal neutrons by the ^{10}B nucleus. The high LET emitted particles deposit their energy in a range of about $10\ \mu\text{m}$, similar to a cell diameter. The fundamental BNCT reaction occurs close to the cell nucleus which increases the probability of DNA breaking, which leads to the death of cancer cells without damaging normal ones [9].

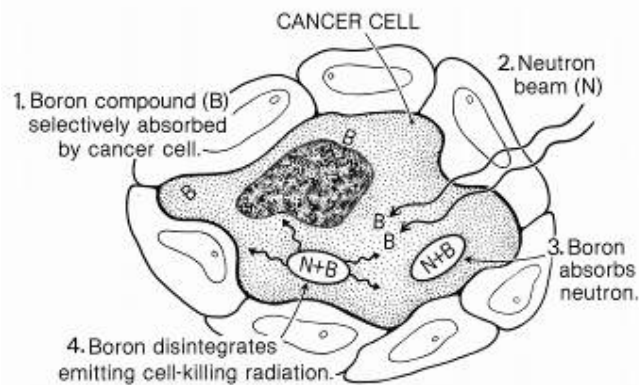


Figure 2. Neutron capture reaction in cancer cell (This image is in the public domain and can be freely reused)

Research about BNCT has also been carried out in Indonesia through a consortium of national research organization entitled Research and Technological Development and Application of Boron Neutron Cancer Therapy (BNCT) with Compact Neutron Generator. This consortium involves a number of institutions, like the National Atomic Energy Agency of Indonesia (BATAN), Ministry of Health, Kimia Farma Ltd., and a number of universities and hospitals [10]. This research is expected to enter preclinical trials in 2019/2020. Prior to the commencement of preclinical trial, studies of the BNCT system by simulations need to be conducted. The simulations could possibly include the neutron beam shaping assembly and its dose evaluation for some types of cancer [6, 11, 12, 13, 14].

Head and neck soft tissue sarcoma is a type of cancer that is difficult to treat with surgical method. The delicate anatomy of the head and neck regions limits the ability to obtain wide surgical margins [2]. A new treatment method is required so that the mechanism for treating this type of cancer can be done without surgery. One such therapy method is BNCT. Before the therapy method can be applied in patients with sarcoma, simulations need to be conducted. Therefore, this study researched about the optimization of beam shaping assembly designs for BNCT based cyclotron 30 MeV and its dosimetry simulation in the head and neck soft tissue sarcoma using Monte Carlo N Particle-X program.

MATERIAL AND METHOD

Neutron Beam Shaping Assembly (BSA) Design

BSA is a system tool that is used to produce the neutron fluxes corresponding to the fluxes of neutrons in BNCT therapy [9, 15]. The neutron energy boundaries for the thermal, epithermal and fast neutron fluxes that are used in this simulation research were 0 to 0.5 keV, 0.5 keV to 40 keV, and 40 keV to 30 MeV respectively. Neutrons produced from a neutron source (accelerator, generator, and reactor) have the very high-energy (fast neutron). A moderation system is needed to produce the neutron flux corresponding to the fluxes of BNCT (epithermal neutrons). A BSA can be composed of several parts including the moderator, reflector, aperture, gamma shielding and thermal neutron filter [9, 16, 17]. A precise analysis of neutron transport through the beam shaping assembly has been performed by an MCNPX code on this research using 1 billion cycles. The general view of the beam shaping assembly configuration is shown in Figure 3.

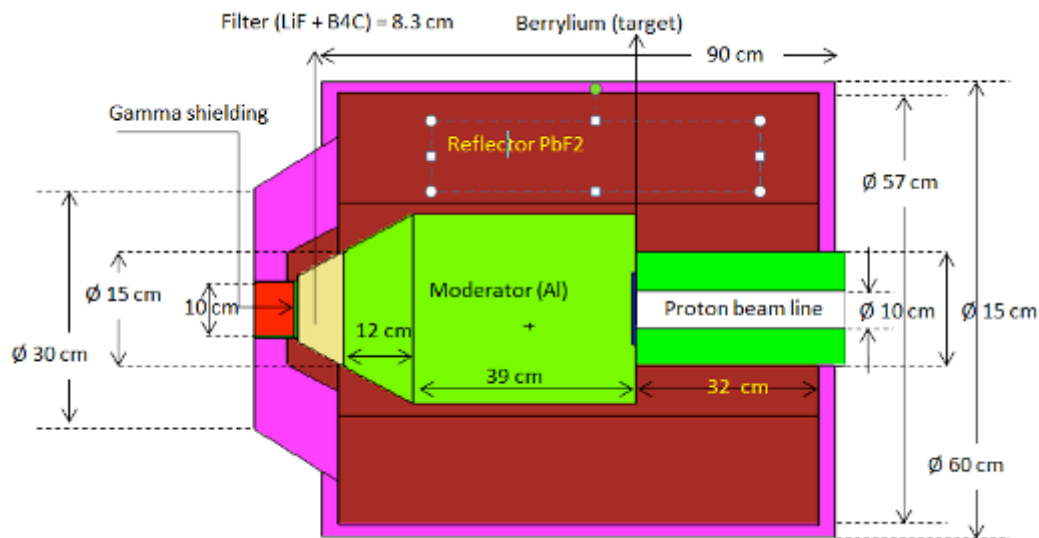


Figure 3. General view of the BSA configuration

Reflector, the best material for a reflector layer should have a high scattering cross-section where the fast neutrons can scatter all neutrons produced by the $\text{Be}(p,n)\text{B}$ reaction, back into the moderator layer in order to produce the epithermal neutrons. Suitable reflector materials are those with a high scattering cross-section and a high atomic mass (resulting in little energy loss). They include Pb, Bi, PbF_2 . These materials are varied in this study to find the best reflector material.

Moderator, a good moderator should have a high scattering cross-section for fast neutrons and a low absorption cross-section for epithermal neutrons. Another consideration is the selected appropriate materials, which require an appropriate mass number. A small mass number causes neutrons to moderate very quickly and thermal neutron contamination increases. On the other hand, if the mass number is large, neutrons cannot release a lot of their energy per collision. Moreover, in the BNCT, a moderator that contains a less radiative capture cross section (n, γ), and less gamma emission in inelastic collisions is needed to avoid harmful gamma radiation to the patient. According to this, MgF_2 , D_2O , CF_2 , Fe, BeO, AlF_3 , Fluenta (69% AlF_3 , 30% Al and 1%LiF), Al and Al_2O_3 were selected as various moderator materials. Various moderator thicknesses were simulated to determine the best moderator material.

Filter, a fast and thermal neutron filter has an important role in absorbing fast and thermal neutrons so that the neutron fluxes coming out of the beam shaping assembly are epithermal neutron fluxes only [18]. Filters in BSA are used to increase the ratio between the epithermal and thermal neutron flux and the ratio between the epithermal and fast neutron flux. This study varied LiF, Li_2O , Mg, MgO , SiC, and CaF_2 as the filter materials.

Gamma shielding, this section serves to absorb the gamma rays in the beam shaping assembly, therefore the chosen materials must have a high density. Recommended materials for gamma shielding are Pb and Bi. Pb has a greater attenuation coefficient than Bi. Nevertheless, Bi can pass more epithermal neutrons than Pb [18].

Aperture, the beam shaping assembly is located at the end of the neutron beam exit. A conical shape of the aperture is created at the end to concentrate the radiation beam toward the target phantom [15]. The aperture beam shaping assembly should be able to reflect the epithermal neutron beam towards the BSA exiting window. The material used for the beam shaping assembly is typically lithium polyethylene [18].

Dosimetry Simulation

Radiation dosimetry can be defined as the study of various quantities and units of radiation doses. The doses are quantized and the results are viewed as radiation on various materials. Dosimetry depends on the energy of radiation and the constituent elements of the material.

Radiation dosimetry can also be understood as a method which is used to determine the amount of radiation energy deposited in a material by direct and indirect ionization. A neutron, when crossing human tissue will interact with the body tissue elements. The type of neutron interactions that occur from those interactions depends on the atoms in the body tissue elements.

There are 4 main doses (called physical dose) that contribute to the treatment of BNCT: the boron dose from the boron neutron capture reaction, the proton dose from the nitrogen capture reaction, the neutron dose, and the gamma dose. The primary dose is Lithium-7 and alpha with 2.79 MeV (6.1%) and 2.31 MeV (93.9%) of energy respectively. The Lithium-7 produced from the decay reaction will revert back to the initial energy level and will emit gamma radiation (0.48MeV). The average energy produced between the interactions of Boron-10 with thermal neutrons is 2.33 MeV.

The secondary dose comes from three interactions. The interaction between fast and thermal neutrons with tissue commonly called neutron scattering. The calculated dose is derived from neutrons scattering due to the reaction between fast and thermal neutrons with Hydrogen-1 nuclei. Protons are recoil products in this interaction. Gamma and hydrogen-2 are produced from the absorption reaction between the neutron interactions with hydrogen contained in body tissue. This produced hydrogen-2 is an excited atom. The production rate of hydrogen-2 from the thermal neutron interaction with hydrogen-1 is proportional to the photon release rate of 2.33 MeV of energy. Nitrogen-14 has a fairly high mass fraction at 4.5% of the tissue mass. Irradiated tissue by thermal neutron leads to the interaction of thermal neutrons with nitrogen-14. This reaction produces carbon-14 and protons with 0.66 MeV of energy. Carbon-14 is a radioactive element with a long half-life of 5730 years.

The weighted total dose (Dt) is defined as the sum of the physical dose components multiplied by the weighting-factors of each dose component in a tissue:

$$Dt = D\gamma.W\gamma + Dn.Wn + Dp.Wp + Db.Wb \quad (1)$$

Where $D\gamma$ is the gamma dose, Dn is the neutron dose, Dp is the nitrogen dose and Db is the boron dose. The weighting factor values for each dose components are given in Table 1. In order to calculate the absorbed dose at various positions, the neutron sources from the BNCT beam shaping assembly design were used. The calculated of gamma-ray dose, proton dose, boron dose and fast neutron absorbed dose were derived from the dose conversion coefficients. The calculations were conducted using F4 tally of MCNPX code combined with DE and DF factor as the value of the dose conversion coefficient for neutron, proton, gamma, and an alpha particle.

Table 1. Weighting factor values for each dose components [15].

Dose	Quality factor	Symbol
Boron	3.8 (cancer)	Wb
	1.3 (healthy)	
Proton	3.2	Wp
Neutron	3.2	Wn
Gamma	1	$W\gamma$

RESULTS AND DISCUSSION

Beam Shaping Assembly Design

Be was chosen as the target material on this study. ^9Be is able to produce the greatest neutron flux when compared to the neutron flux generated by other materials like ^7Li , ^{181}Ta and ^{184}W . Additionally, it has a higher melting and boiling point than ^7Li [19]. Table 2 shows the target material characteristics for ^9Be , ^7Li , ^{181}Ta and ^{184}W . Calculations show that the beam shaping assembly design produces 1.33×10^{11} n/s cm^{-2} of total neutron fluxes on a 19 cm target diameter with a 0.5 cm thickness. The total neutron fluxes consist of 9.15×10^7 n/s cm^{-2} of thermal neutron

flux, 1.05×10^{10} n/s cm^{-2} of epithermal neutron flux, and 1.23×10^{11} n/s cm^{-2} of fast neutron flux. The total neutron flux will be moderated in the designed beam shaping assembly to produce a neutron flux which is suitable for BNCT system.

Table 2. Target material characteristics as neutron sources [19].

Target	Melting point ($^{\circ}\text{C}$)	Boiling point ($^{\circ}\text{C}$)	Thermal conductivity (W/mK)	Neutron yield (n/smA)	Gamma-ray per one neutron
Li	180	1340	84.7	1.14×10^{14}	0.09
Be	1278	2970	201	1.90×10^{14}	0.02
Ta	3017	5448	57.5	1.27×10^{14}	0.93
W	3422	5555	174	9.65×10^{14}	1.40

The neutron flux used for BNCT system is the epithermal neutron flux. To obtain the epithermal neutron flux, the total fluxes of neutron are moderated by various moderator materials in the beam shaping assembly design. The total neutron fluxes generated from the ${}^9\text{Be}(p, n){}^9\text{B}$ reaction have various trajectories. So, a neutron reflector is needed to steer the neutron flux to the moderation room. Various materials were simulated as reflector materials in this study. The output is given in Figure 4. Based on Figure 4, PbF_2 is the best material to be chosen as the reflector. Our criterion for choosing the best reflector material is based on each material's capability to reflect the greatest number of neutrons. In addition to the moderator and reflector, the beam shaping assembly design is also fitted with filters to reduce the fast neutron flux, thermal neutron flux, and its gamma contamination.

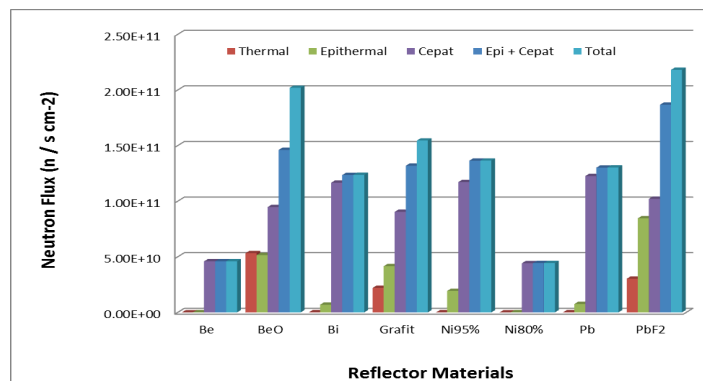


Figure 4. Results of various materials used as reflectors

Tally type F4 was used to obtain the thermal, epithermal, and fast neutron flux in the moderator layer. Various materials such as Al, Al_2O_3 , AlF_3 , CaF_2 , Fe, LiF, MgF_2 , Ni, and Pb were simulated as moderator material. The results of the simulations are shown in Figure 5.

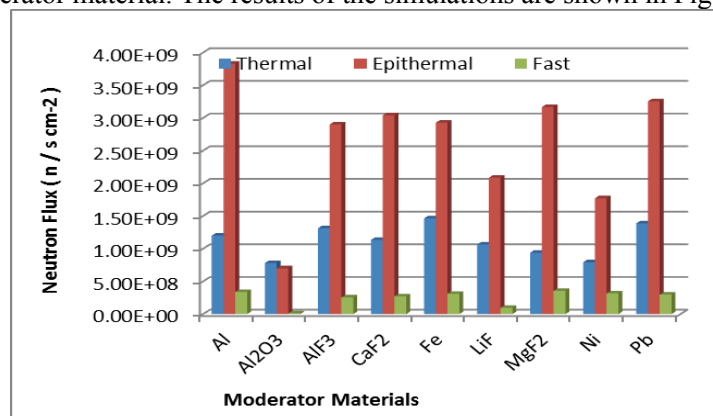


Figure 5. Thermal, epithermal, and fast neutron flux in the moderator layer

According to the results shown in Figure 5, the best moderator material is aluminum. It generated the highest epithermal neutron flux with low fast neutron contamination. Therefore, aluminum was chosen as the moderator material in this study. The study was continued in several simulations to discover the optimal neutron filter and gamma shielding materials. 12 cm CaF₂, 0.3 cm B₄C, and 0.5 cm Pb were chosen as the fast neutron filter, thermal neutron filter, and gamma shielding respectively. The beam shaping assembly design used in this simulation to determine the neutron flux which is suitable for BNCT system is shown in Figure 6. Table 3 shows the neutron flux characteristics as the output of the simulation calculation of the beam shaping assembly design. Pb material with 11 cm in diameter was chosen as the aperture parameter.

Table 3. Neutron flux characteristics as the output of the final calculations

Parameters	Unit	Optimization results	IAEA standard
Epithermal neutron flux	$\Phi_{\text{epi}} (n / s \text{ cm}^{-2})$	2.83×10^9	$> 1.0 \times 10^9$
Fast neutron dose rate to epithermal neutron flux ratio	$D_f / \Phi_{\text{epi}} (Gy - \text{cm}^2 / n)$	9.80×10^{-14}	$< 2.0 \times 10^{-13}$
Gamma dose rate to epithermal neutron flux ratio	$D_\gamma / \Phi_{\text{epi}} (Gy - \text{cm}^2 / n)$	2.53×10^{-14}	$< 2.0 \times 10^{-13}$
Thermal neutron to epithermal neutron flux ratio	$\Phi_{\text{th}} / \Phi_{\text{epi}}$	0.038	< 0.05
Epithermal neutron current to flux ratio	$\Phi_{\text{epi}} / J_{\text{epi}}$	0.879	> 0.7

Dosimetry Simulation

This study was started by simulating the ORNL neck phantom model using the MCNPX code. A cancerous tissue was then placed on the left side of the neck phantom model. The cancerous tissue is divided into three parts (Figure 6), namely the Planning Tumor Volume (PTV), Clinical Tumor Volume (CTV), and the Gross Tumor Volume (GTV). GTV is an area that is detected as the primary cancer site with the greatest density of cancer cells. The CTV is the GTV area coupled with the volume area around the GTV where suspected spreading of cancer cells occurred. PTV is a CTV area coupled with additional limits on the movement or deformation of cancer cells. The limitations of GTV, CTV, and PTV are determined by oncologists based on the biological characteristics of the cancer tissues [20].

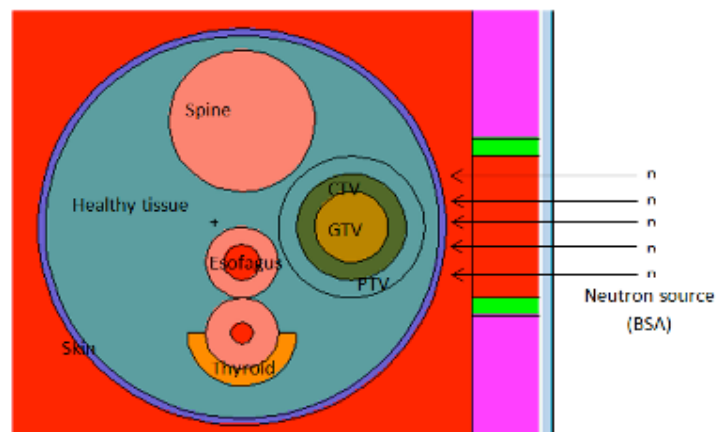


Figure 6. ORNL neck phantom model in the lateral view

The 2.83×10^9 n/s cm⁻² of thermal neutron flux are pointed to irradiate the neck phantom model and then will passed through a moderation process in the neck phantom model tissues. The greater the depth of the neutron flux is transported in the tissue, the greater the thermal neutron flux

will be produced. Figure 7 presents a graph of neutron flux characteristics when passed through the neck phantom model tissues. The number of thermal neutron flux is peaked at an approximate depth of 40 up to 60 mm from the surface of the skin. The amount of thermal and epithermal neutron flux is decreased on subsequent depths.

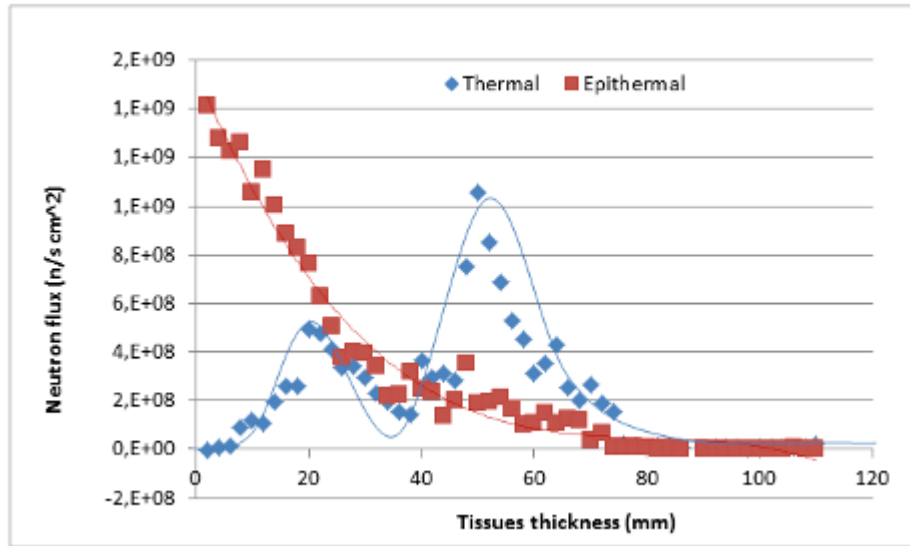


Figure 7. Neutron flux characteristics when passed through the neck phantom model tissues

The graph presented in Figure 8 shows the dose rate characteristics in each tissue in the neck phantom model. The highest value of the dose rate is found in the cancerous tissue (GTV). GTV contains the highest boron concentration for each dose rate variation simulation and it has a higher dose rate than other healthy tissue.

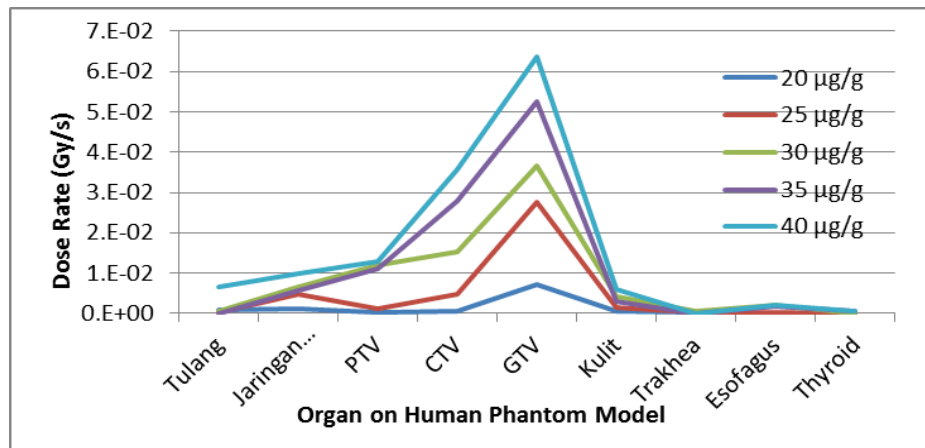


Figure 8. Dose rate characteristics in each tissue in the neck phantom model

The total weighted dose required to manage a pre-operative soft tissue sarcoma is 50 Gy. In the BNCT treatment method, a neutron radiation system was planned in a single fraction. In a single fraction method, the radiation treatment will be carried out by a single radiation dose. Since the dose of radiation needed to kill the cancerous tissue must be large enough, it is necessary to calculate and determine the affects of dose on other tissues, such as skin and healthy tissues in the ORNL neck phantom model. The total dose is obtained by multiplying the radiation dose rate with the time needed to administer a 50 Gy total dose. Table 4 presents the time needed to deliver a 50 Gy total dose in cancer tissue.

Table 4. Treatment time for each boron concentration variations in neck ORNL phantom model

Boron concentration ($\mu\text{g/g}$)	Total Dose (Gy)			Treatment times (t)
	GTV	Healthy tissues	Skin	hour
20	50	10	6	2
25	50	9	6	0.5
30	50	8	4	0.4
35	50	7	3	0.3
40	50	6	3	0.2

CONCLUSION

Two main objectives were investigated in this simulation study. First, this study aims to design a neutron BSA which is suitable for a BNCT system. The second goal is to calculate the neutron fluxes and dosimetry system of BNCT in the head and neck soft tissue sarcoma (STS). All simulations were performed using the MCNPX, a Monte Carlo radiation transport code for both the neutron beam shaping assembly design and dosimetry evaluations. The neutron BSA was designed to be used in treating a head and neck STS cancer to find out the BNCT irradiation time. The thermal neutron dose, including the boron and nitrogen doses, fast neutrons as well as photon doses have been investigated to find out the total dose of this treatment method. To perform these calculations, kerma investigations for all particles are included. Finally, the total dose and treatment time to treat a head and neck soft tissue sarcoma in the ORNL neck phantom model has been calculated.

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