EVALUATION OF RADIATION TRANSPORT AND DOSE DISTRIBUTION IN BORON NEUTRON CAPTURE THERAPY USING PHITS

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Abstract— **Monte Carlo simulation is used to accurately model a complex radiation transport and dose distributions in Boron Neutron Capture Therapy. BNCT is a type of radiation therapy that uses the interaction of boron and slow neutrons to destroy cancer cells without harming the healthy tissues. This study aims to track millions of particle interactions such as photon, boron, nitrogen and hydrogen via random sampling using Particle Heavy Ion Transport code System (PHITS). The boron concentration was varied from 10-100 µg/g tissue. The cancer geometry was divided into three volumes (Gross Target Volume, Clinical Target Volume, and Planning Target Volume). To ensure an accurate radiation transport and dose distribution, the material compositions were selected from NIST and ICRP 110. The alpha particle and lithium-7 particle flux from the interaction of thermal neutron and boron are restricted to the cancer geometries. This result validates that concept that BNCT can selectively destroy the cancer cells while sparing the healthy tissues. The results showed that increasing boron concentration increases the boron dose, while decreasing the nitrogen dose and photon dose. Lastly, the hydrogen dose stays the same because the hydrogen content in the material composition is almost identical.**

Keywords— **BNCT, PHITS, Dose distribution**

I. INTRODUCTION

The discovery of the interaction between boron-10 and slow neutron, which results in energetic particles that can destroy cells, gave rise to Boron Neutron Capture Therapy in the 1930s [1]. BNCT is a radiation method that delivers a high radiation dose to tumour cells while minimizing damage to surrounding healthy tissue and it is a benign method for treating malignant tumours [2]. BNCT depends on two phenomena. First, the tumour tissue is injected with a non-radioactive boron medication. After then, the patient is exposed to epithermal neutrons until the normal tissue dose limit is reached. When the nonradioactive boron atom captures the thermalized neutron, a decaying process occurs in which the thermalized neutron decays via short-range particles and recoils the Li-7 nucleus [3]. This energy has the power to locally destroy the cancerous cell containing the boron drugs while causing no harm to the surrounding healthy tissue. To achieve a decent result, two parameters need to be considered: boron concentration and neutron beam [2]. Thermal neutrons are the most important for BNCT because they initiate the Li capture reaction. However, because they have a limited depth of penetration, epithermal neutrons, which lose energy and fall into the thermal range as they penetrate tissues, are now preferred for clinical therapy. Several reactors with very good neutron beam quality have been developed and currently are being used clinically [4].

Dosimetry in BNCT is complex since the total absorbed dose is a mixture of different radiation components with different weighting factors [5,6]. These dose components are generally: boron dose, photon dose, nitrogen dose, and hydrogen dose.

Monte Carlo simulation has been used extensively in medical physics for research in radiotherapy, dose analysis, dosimetry, and advanced clinical applications [7]. Several Monte Carlo codes have been extensively utilized in evaluating BNCT such Particle Heavy Ion Transport code System (PHITS), and Monte Carlo N-Particle Transport code (MNCP) to model the complex interactions of neutrons, gamma rays, and other particles within the human tissue to calculate the dose delivered to the cancerous tissues compared to the normal tissues [8].

The BNCT dose calculations in PHITS includes implementing Gross Target Volume, Clinical Target Volume, and Planning Target Volume regions in your simulations, calculating the four dose components in namely boron dose, proton dose, gamma dose and neutron dose.

This study utilizes PHITS to model the dose distribution in brain cancer and to investigate how variation of boron concentration influences the four doses in BNCT simulation.

II. METHODOLOGY

It is necessary to build the geometry model before doing a simulation for BNCT. This study was conducted using the Monte Carlo simulation software PHITS version 3.341 in HP Laptop 15-fd0xxx [9]. The process of the research simulation is shown in Fig. 1.

The variation of boron concentrations was varied from 10-100 µg/g, and increment of 10. The neutron source used in the simulation is an epithermal neutron with a 10 keV energy. The neutron source was ensured to be directed

towards the target regions that contains the boron concentrations.

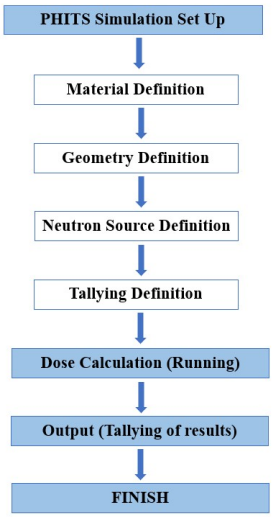

Fig. 1 Flow chart of the simulation approach

For accuracy purposes, the material compositions used in the simulation are brain, bone, skin and cerebral spinal fluid (CSF) which were derived from the elemental composition provided by National Institute of Standard and Technology and ICRP 110 [10,11].

The cancer was divided into three regions, namely, Gross Target Volume (GTV), Clinical Target Volume (CTV) and Planning Target Volume (PTV) and the radii for each part were 2.5, 3.0 and 3.5 cm, respectively. The ratio of the boron concentration in the target regions was 10:5:1.

Table 1 Mass fraction of the normal tissues provided by NIST and ICRP110

Material Composition	Mass Fraction			
	Brain	Bone	Skin	CSF
Hydrogen	0.110667	0.110667	0.100588	0.11000
Carbon	0.125420	0.125420	0.228250	
Nitrogen	0.013280	0.013280	0.046420	
Oxygen	0.737723	0.737723	0.619002	0.89000
Sodium	0.001840	0.001840	0.000070	
Magnesium	0.000150	0.000150	0.000060	
Phosphorous	0.003540	0.003540	0.000330	
Sulfur	0.001770	0.001770	0.001590	
Chlorine	0.002360	0.002360	0.002670	
Potassium	0.003100	0.003100	0.000850	
Calcium	0.000090	0.000090	0.000150	
Iron	0.000050	0.000050	0.000010	
Zinc	0.000010	0.000010	0.000010	

The tallying functions used in the simulation for different types of dose calculation of the four doses (boron, photon, nitrogen and hydrogen) are t-track. The number of batches (maxbch) and particles per batch (maxcas) depends on the required accuracy and computational power. More batches help improve statistical averaging of the simulation and more particles per batch reduce the variance in scoring [12]. For high precision and accuracy, it is recommended to use 10 million neutron histories for BNCT simulation.

III. RESULTS AND DISCUSSION

In Fig. 2, region one to three are the target volumes. Region 1 is the Gross Target Volume where most of the cancer is located, region 2 is the Clinical Target Volume which comprises of 50% of the cancer cells, and region 3 is the Planning Target Volume which is just a marginal part of the cancer. The rest of the layering regions are the normal regions (brain, bone, Cerebral Spinal Fluid and skin). As seen Fig. 2, the combined flux map distribution of alpha particle and Lithium-7 is severely restricted to the target volumes where the boron is located. This is due to their short range of these particles which validates the selective generation of high-LET particles at the boron-loaded region.

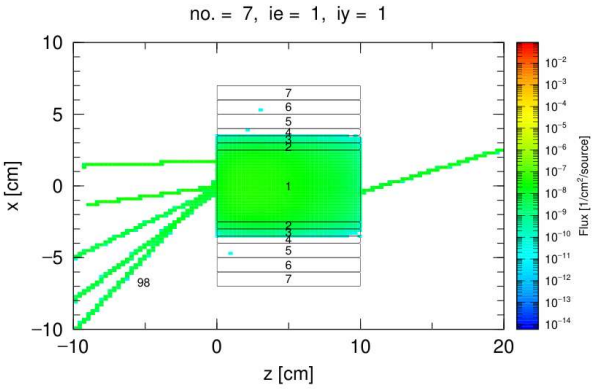

Fig. 2 Alpha + lithium-7 particle flux map distribution in r-z mesh

The simulated boron dose per source which selectively hits the tumour came from the high-LET alpha particle and lithium-7 recoil produced from boron capture. The photon dose came from the prompt captures of gamma (mainly boron and hydrogen) and other reactions contributing to a low-LET, whole body background dose). The hydrogen is mainly from the recoil of protons created by fast neutron scattering on hydrogen. Nitrogen is from the energetic protons emitted from carbon 14. The simulated boron, nitrogen, photon and hydrogen dose are shown in Figures 3, 4, 5, and 6 respectively.

In BNCT, the simulated doses are the calculation of the absorbed energy transmitted to a tissue. As seen in Fig. 3,

the simulated boron dose in Gross Target Volume, Clinical Target Volume and Planning Target Volume increases as the boron concentration is increased as the dose is directly proportional to the boron content within the cancerous cells. Increasing the boron concentration will lead to a larger fraction of neutron that creates an alpha particle and a lithium nucleus, and these particles produce a charge particle, hence the dose shifts toward a less gamma dose.

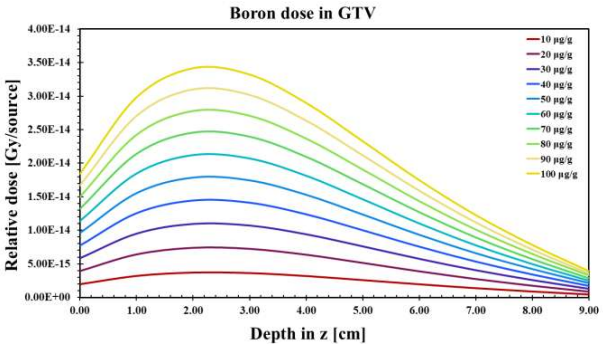

Fig. 3 (a) Boron dose at GTV (assumed to have 100% concentration)

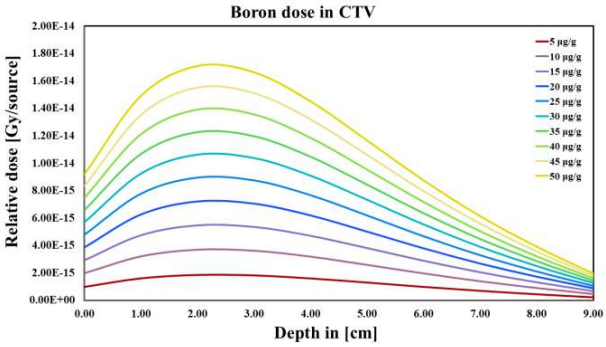

Fig. 3 (b) Boron dose at CTV (assumed to have 50% concentration)

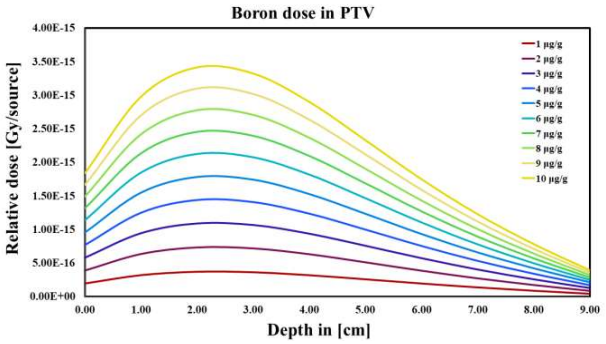

Fig. 3 (c) Boron dose at PTV (assumed to have 10% concentration)

Thus, as seen in Figure 4, the photon dose decreases with increasing boron concentration. Gamma rays are likely to be absorbed as tissues with high boron concentration have a slightly higher density and slightly higher gamma attenuation coefficient. Additionally, increasing the boron concentration produces more epithermal neutrons to thermal neutrons.

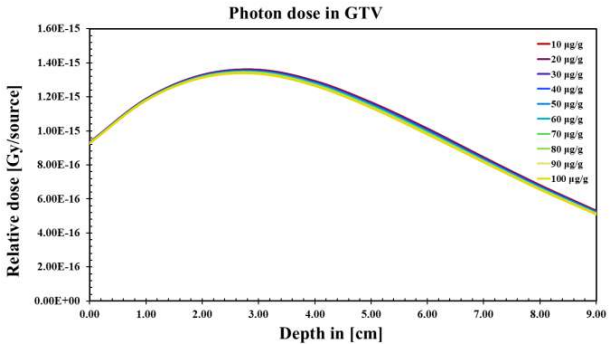

Fig. 4 (a) Photon dose at GTV (assumed to have 100% concentration)

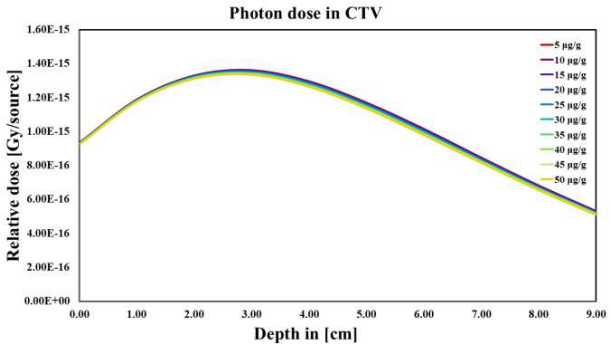

Fig. 4 (b) Photon dose at CTV (assumed to have 50% concentration)

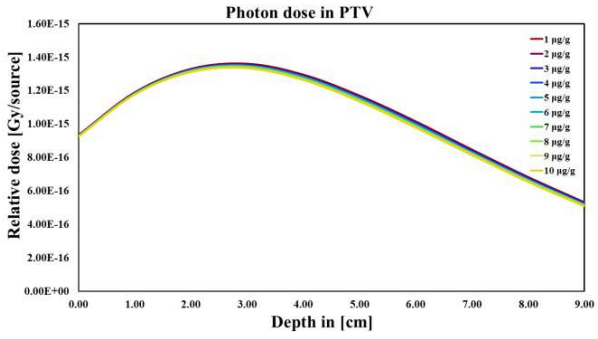

Fig. 4 (c) Photon dose at PTV (assumed to have 10% concentration)

This interaction causes an increase of nitrogen dose when the boron concentration is increased as seen in Fig. 6. Meanwhile, the hydrogen dose (see Fig. 5) does not change, or the changes is barely seen in the figure.

The hydrogen dose comes from the elastic scattering of neutron which produces proton recoil. This is because the hydrogen contents within the materials and the density of the materials are almost the same. Hydrogen dose depends on the density of the material, neutron flux specifically for fast neutron. So, when boron concentration is increased, the hydrogen dose stays almost identical.

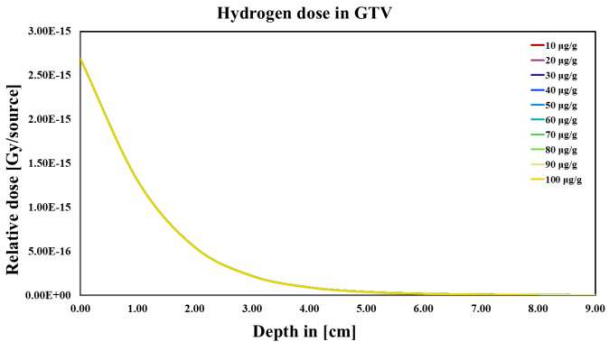

Fig. 5 (a) Hydrogen dose at GTV (assumed to have 100% concentration)

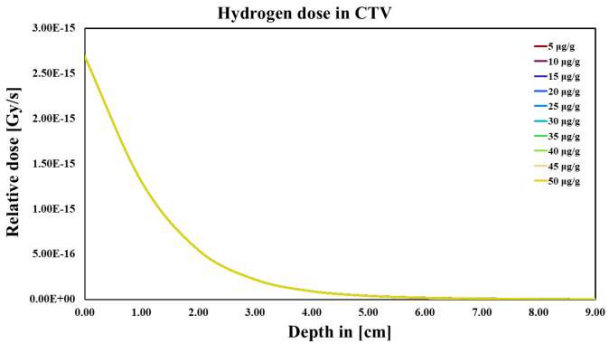

Fig. 5 (b) Hydrogen dose at CTV (assumed to have 50% concentration)

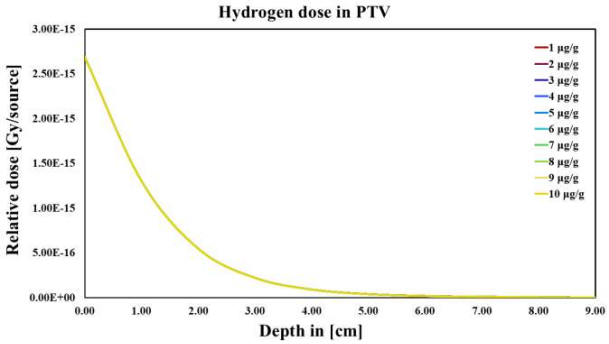

Fig. 5 (C) Hydrogen dose at PTV (assumed to have 10% concentration)

Nitrogen is naturally present in a human body; they could be protein or even in DNA. Similarly, the nitrogen dose decreases with increasing boron concentration due to the fact that boron is ten times more attractive than nitrogen, which tends for neutron to interact with boron before they can interact with nitrogen atom. These results and observation are similar to photon wherein increasing boron concentration decreases the photon dose.

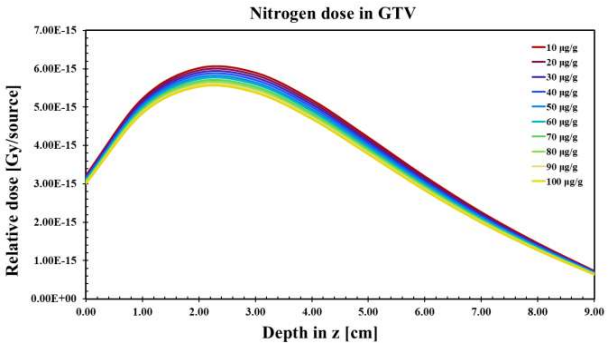

Fig. 6 (a) Nitrogen dose at GTV (assumed to have 100% concentration)

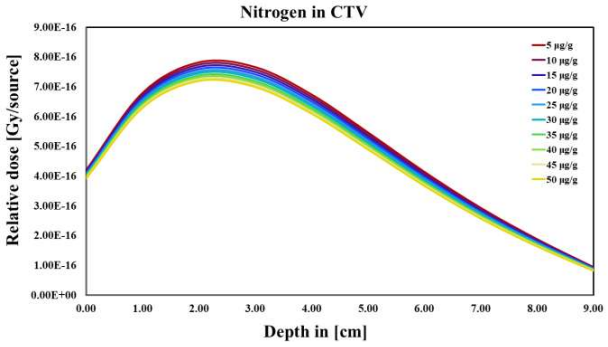

Fig. 6 (b) Nitrogen dose at CTV (assumed to have 50% concentration)

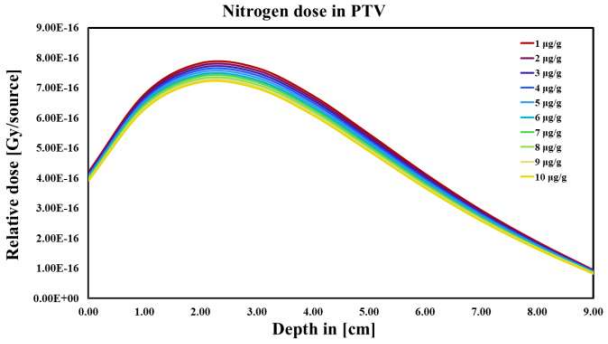

Fig. 6 (c) Nitrogen dose at PTV (assumed to have 10% concentration)

These following observations are all the same in the defined target volumes in the cancer geometry. However, in the normal tissues defined in the simulation (brain, CSF, bone and skin), changes are not seen in the boron dose, nitrogen dose, photon dose and hydrogen dose. This is because those tissues are assumed to be normal tissues and ensured that they will not be affected by the irradiation.

IV. CONCLUSIONS

The simulation result demonstrates a clear correlation between the boron-loaded regions and the generation of the therapeutic particles. The analysis from the r-z mesh flux maps validates the microscopic selectivity of BNCT as the high-LET alpha and lithium-7 particles are restricted to the target volumes while sparing the normal tissues. This is due to the short range of these particles (approx. 5-9 μm); thus, the nuclear reaction is within the area where the cancer is located [13]. The correlation of boron concentration to the four doses in BNCT were investigated thoroughly. The boron dose and boron concentration has a linear correlation which demonstrates that higher boron uptake significantly increases the destruction of the cancer cells. In contrast, increasing the boron concentration decreases the photon and nitrogen dose. Lastly, the stability of the hydrogen dose is from the fast neutron recoils which remains unchanged as the concertation is increased. These results demonstrates that increasing boron concentration provides secondary benefit sparing the healthy tissues from destructive doses from the nuclear reaction of boron and slow neutron. These results suggest that a higher boron-to-tissue ratio significantly improves the therapeutic gain without increasing the fast neutron background.

V. ACKNOWLEDGMENT

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VI. REFERENCES

1. Barth R. F, Zhang Z, Liu T (2018) A realistic appraisal of boron neutron capture therapy as a cancer treatment modality. Cancer Communications. pp. 1-7
2. Anderson B. A, Bagaswoto P (2018) Overview of boron neutron capture therapy: a medical aspect. ASEAN Journal on Science and Technology for Development, vol. 35, no. 0217-5460, 217-221
3. Horiguchi H, Sato T, Kumada H, et al (2014). Estimation of relative biological effectiveness for boron neutron capture therapy using PHITS code coupled with a microdosimetric kinetic model. Journal of Radiation Research, 56(2), 382-390
4. Kumada H, Takada K (2018) Treatment planning system and patient positioning for boron neutron capture therapy. Therapeutic Radiology and Oncology, 2, 50-50.
5. Barth R. F, Gupta N, & Kawabata S, (2024) Evaluation of sodium borocaptate (BSH) and boronophenylalanin (BPA) as boron delivery agents for neutron capture therapy (NCT) of cancer: An update and a guide for the future clinical evaluation of new boron delivery agents for NCT. Cancer Communication.
6. Wang S, Zhang Z, Miao L, et al (2022). Boron neutron capture therapy: current status and challenges. Frontiers in Oncology, vol. 12.
7. Shields J (2022) A review on monte carlo methods and their application in medical physics for simulating radiation transport. Honors Theses and Capstones. 657
8. Seco J, and Verhaegen F (2021) Monte carlo techniques in radiation therapy: applications to dosimetry, imaging, and preclinical radiotherapy. Biomedical Engineering
9. Sato T, Niita K, Matsuda N, et al (2022) Particle and Heavy Ion Transport code System (PHITS), version 3.34 User's Manual. Japan Atomic Energy Agency
10. International Commission on Radiological Protection, (2009) Adult Reference Computational Phantoms, Annals of the ICRP 39
11. National Institute of Standard and Technology (2025), Atomic Weight and Isotropic Compositions with Relative Atomic Masses at https://www.nist.gov/pml/atomic-weight-and-isotropic-compositions-relative-atomic-masses
12. Uyar E, Gunekbay Z (2023) Comparison of the number of particle history for monte carlo codes in gamma-ray spectroscopy. Journal of Science, Part A, 10(2): 176-183
13. Nedunchezhian K, Aswath N, Thiruppathy M, et al (2016). Boron neutron capture therapy - a literature review. Journal of Clinical and Diagnostic Research. pp. 1-4

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