Beam Neutron Optimization for Boron Neutron Capture Therapy (BNCT) facility

Lekkaa Salah[1], **R.M.M. Mahmoud[2]**, M.M. Ahmed[3], R.A. Rizk[3], Moustafa Aziz[2]

1. High Institute of Engineering at 15 May City, **2. Nuclear and Radiological Safety Research Center, Egyptian Atomic Energy Authority, Cairo, Egypt** 3. Faculty of Since, Helwan University

randam76@yahoo.com - +201100394044

ABSTRACT

The present work is focused on the design and optimization of a beam shaping assembly (BSA) for boron neutron capture therapy (BNCT) facility based on a proton accelerator. The beam shape assembly optimization is simulated by MCNP Monte Carlo code. The geometry design of beam shaping assembly is consists of a set of materials used as moderator, reflector, neutron filter and gamma filter. The output neutron beam characteristics are compared to that recommended by the international atomic energy agency (IAEA). The dose components that contributed to the absorbed dose are simulated using MCNP code based on the neutron interactions mode and boron concentration values taking into account the Relative Biological Effectiveness (RBE) factors. The total effective dose in brain tumor and healthy tissues for different values of ^{10}B concentration are compered to calculate the therapeutic gain (TG).

INTRODUCTION

The boron neutron capture therapy (BNCT) is a new and efficient form of radiotherapy treatment that allows for the targeted radiation dosing of cancerous cells, while avoiding most healthy cells unaffected. BNCT uses boron-10's nuclear reaction to target cancer cells, minimizing harm to surrounding tissues which offers better radiation damage control compared to traditional therapies [1]. Delivery agents delivering boron specifically to cancer cells and not healthy cells is crucial for treatment success, Also neutron production and irradiation factors are key considerations. A neutron beam facility for BNCT should have high beam purity, intensity, and a well-shielded irradiation room with reliable patient viewing and control systems to prevent unintentional exposure. Accelerator-based BNCT (AB-BNCT) is actively researched as a substitute for reactor-based BNCT due to its advantages. AB-BNCT systems consist of a proton accelerator, a target for the proton beam, a beam shaping assembly, and neutron beam lines for clinical work. By optimizing the design of the BSA, the neutron yield can be further improved [2-3].

AIMOF THE WORK

The aim of this study is to **design a suitable neutron beam**, for AB-BNCT system, both in terms of energy and flux, using BSA based on IAEA recommendation values using Monte Carlo simulation in order to facilitate that system's application in medical centers. A simulation of the dose components that contributed to the **absorbed dose** based on the neutron interactions modes and values of ^{10}B concentration is done. **The total effective dose** in brain tumor and healthy tissues is calculated taking into account the relative biological effectiveness (RBE) factors, and different values of ^{10}B concentration to determined the **therapeutic gain (TG)**.

MATERIALS AND METHODS - Beam Shape Assembly Design

BNCT is a novel modality of radiation cancer therapy. Boron compounds are administered to tumor cells, followed by thermal neutron irradiation, inducing the ^{10}B (n, α)^{7}Li nuclear reaction

$$^{10}B + n_{th} \rightarrow {}^{11}B \rightarrow {}^{4}He\ (1.78\ MeV) + {}^{7}Li\ (1.01\ MeV)\ (6.3\%) \quad (1)$$

$$^{10}B + n_{th} \rightarrow {}^{11}B \rightarrow {}^{4}He\ (1.47\ MeV) + {}^{7}Li\ (0.84\ MeV) + \gamma(0.48\ MeV)\ (93.7\%)$$

Both α particles and ^{7}Li nuclei deposit their energies along their very short paths, which are comparable to the size of cells. As a result, tumor cells are destroyed accurately without harming healthy tissues [4,5]. Different studies have **identified the optimal boron agent drug** [1, 5, 6] with high selectivity for cancer cells. It exhibits high tumor uptake, maintains ^{10}B concentrations in tumor tissues during neutron irradiation, rapidly clears from normal tissues and blood, and has low toxicity while meeting international pharmaceutical requirements. The compact accelerator-based neutron source (CANS) technology as BNCT potential cancer treatment is generates neutrons by bombarding a light element target, such as beryllium or lithium, with low-energy protons. This study propose a neutron beam is generated by accelerating protons and directing them at **a 0.6 cm** thick **beryllium** target. The neutron yield from the reaction is **2.81×10^{14}** and the energy distribution is based on measurements by M. A. Lone et al. [13]. and incorporated into code input. BSA functions include slowing-down fast neutrons to epithermal or thermal neutrons, reducing fast neutron, thermal neutron, and γ ray components, and collimating neutron beam. BSA design aids in generating thermal neutron for treating superficial lesions and epithermal neutron for treating deep ones.

IAEA's recommendations for BNCT neutron beam quality are outlined in IAEA-TECDOC-1223. Table 1 showcases desired values for neutron flux, gamma ray ratio, and fast neutron doses for tumor treatments.

Table 1: BNCT neutron beam characteristics recommended in IAEA-TECDOC-1223

Specified BNCT Parameter	Recommended values
Epithermal neutron flux	> 5 x 108 n/cm2s
Thermal neutron ratio	> 0.05
Gamma ray dose per epithermal neutron	1 to 13 x 10-13 GY cm2/$n_{epithermal}$
Fast neutron dose per epithermal neutron	2.5 to 13 x 10-13 GY cm2/$n_{epithermal}$
Current /Flux ratio	< 0.7

The BSA design is simulated using MCNP5 code to simulate neutron, photon, and electron transport probabilities. It includes fission reaction, scattering, and absorption. The MCNP Multiple simulation studies different thicknesses and configurations for BSA material composition optimization as the following: **1. Reflector** material used to reflect scattered neutrons and act as a collimator. It should have low absorption, high elastic scattering, and substantial mass to minimize energy loss. **Pb** is commonly used in BNCT systems as it fulfills these requirements [7-9]. **2. Moderator** material which characterized by low scattering cross section, high removal cross section, minimal radioactive neutron and gamma captures, and no substantial gamma ray production [4-7], such as **Fluental, CF_2, D_2O, MgF_2, Al_2O_3, ^{7}LiF, AlF_3, TiF_3, BeD_2, BeO_2, and CaF_2, and 3. Neutron and gamma filters** to achieve an appropriate neutron beam for BNCT, as a filters for fast neutrons, thermal neutrons, and gamma rays are necessary. Materials like **^{60}Ni** can be used as a fast neutron filter. **Cd** or **Li** are suitable for filtering thermal neutrons without absorbing a significant amount of epithermal neutrons. **Pb** is an excellent gamma ray filter, but it reduces the intensity of epithermal neutrons. **Bi** is a preferable choice to attenuates photons without absorbing epithermal neutrons [10-12].

MATERIALS AND METHODS - Head model and dose calculation

In BNCT, the absorbed dose in healthy tissues is influenced by neutron scattering and capture reactions in the brain, the contribution of neutron scattering to the secondary dose on healthy tissues as it thermalizes through tissues. The total absorbed dose in tissue, in BNCT, can be expressed as follows:

$$D_T = D_B + D_n + D_p + D_\gamma \quad (2)$$

Each component of the total absorbed dose is associated with different nuclear reactions: **1.The boron dose D_B,** is from ^{10}B (n, α) ^{7}Li reaction - **2.The neutron dose D_N**, is from ^{1}H (n, n')^{1}H reaction – **3.The Proton dose D_P**, is from ^{14}N (n, p)^{14}C reaction and **4.The gamma dose D_γ,** is from ^{1}H (n, γ) ^{2}H reaction and the residual gamma from ^{10}B capture reaction ^{10}B (n, γ) ^{7}Li. These doses are calculated based on the ionization energy released by the particles involved in the respective reactions. **The Biological dose** can be calculated using RBE factors, considering effectiveness of each component, by multiplying absorbed dose by RBE. as following [14-17]:

$$D = w_c * D_B + w_n * D_n + w_p * D_p + w_\gamma * D_\gamma \quad (3)$$

were: w_c, w_n, w_p, w_γ are the relative biological effectiveness weighting factor for boron, neutron, proton and gamma respectively. The biological dose is still an active field of research in the BNCT community.

The **head model** is performed based on spherical cancer **tumor** with **4.1 cm** radius located in the front center of the brain at a distance **of 0.9 cm** from the skull. The investigation of the dose distribution on the head model included the skin, skull, health brain cells and brain cancer tumor.

Neutron flux for different energy groups, neutron and gamma dose are tallied with histories of $10^7 – 10^8$ particles considering the human head with a brain tumor are simulated using the material elemental composition and density recommended by ICRU-46 [18] which illustrated at table 2.

Table 2: Materials elemental compositions used for head phantom in simulation [18]

Tissue	Density (gm/cm^3)	H	C	N	O	Na	Mg	P	S	Cl	K	Ca
Skin	1.12	10	20.4	4.2	64.5	0.2	-	0.1	0.2	0.3	0.1	-
Skull (Bone)	1.935	5	21.2	4	43.5	0.1	0.2	8.1	0.3	-	-	17.6
Brain	1.04	10.7	14.5	2.2	71.2	0.2	-	0.4	0.2	0.3	0.3	-

Boron concentrations in tumor cells and healthy tissues are assumed in a ratio of 4:1 [19, 20] ranging from 10 ppm to 50 ppm. Effective doses for brain tumors and healthy tissue are calculated using simulated doses and RBE factors illustrated in table 3 [14, 21]. The determination of TG is essential in BNCT. TG is calculated by dividing the total effective dose delivered to the tumor region by the maximum effective dose delivered to healthy tissues [22], for different for different values of ^{10}B concentration. ^{10}B concentration based on the specific geometry and position of the cancer target.

Table 3: RBE factors used for different dose components

Tissue	Tumor	healthy tissue
w_c	3.8	1.32
w_p	3.2	3.2
w_n	3.2	3.2
w_γ	1	1

Results and Discussion - Beam Shape Assembly Design

Different simulations with MCNP5 code used various materials and arrangements to optimize neutron beam quality and satisfy IAEA recommendation. Figure (1) shows the final BSA model and human head model configuration.

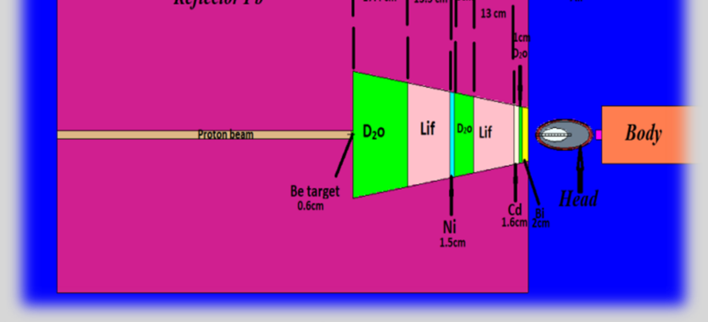

Figure (1): Final BSA model geometry configuration design and a human head model.

The energy spectrum of the neutron source obtained from BSA performed simulation model is 1.18E+9, 2.17E+8 and 4.16195E+8 n/cm2s for flux of epithermal, thermal and fast neutron respectively, with estimated uncertainty values are generally reliable confidence in the Monte Carlo results [23]. The results of the BSA model are compared to the neutron beam criteria recommended by the IAEA to ensure beam therapy quality, and it is illustrated in table 4 that the resulted BNCT neutron beam characteristics are compatible with the neutron beam criteria recommended by the IAEA. The thermal ratio may be more suitable to treat superficial tumors as mentioned by Guangru Li et.al. [24].

Table 4: Comparison between the resulted BNCT neutron beam characteristics and the neutron beam criteria recommended by IAEA.

BNCT neutron beam characteristics	$\emptyset_{epi}$ (n/cm^2s)	$\emptyset_{Th}/\emptyset_{epi}$	$D_F/\emptyset_{epi}$ (GY $cm^2/n_{epithermal}$)	$D_\gamma/\emptyset_{epi}$ (GY $cm^2/n_{epithermal}$)
IAEA recommendation	$> 5 \times 10^8$ n/cm^2s	< 0.05	1 to 13×10^{-13}	2.5 to 13×10^{-13}
BSA Model Results	1.18E+9	0.18	7.08E-13	1.89E-13

Results and Discussion - Head model and dose calculation

The results of head irradiation simulation model before ^{10}B injection is shown in the next figure (2) , it illustrate that the higher thermal flux is in tumor cells at depth 4.2 cm and epithermal and fast flux decreases along the head depth due to continuous slowing down inside the tumor cell tissues.

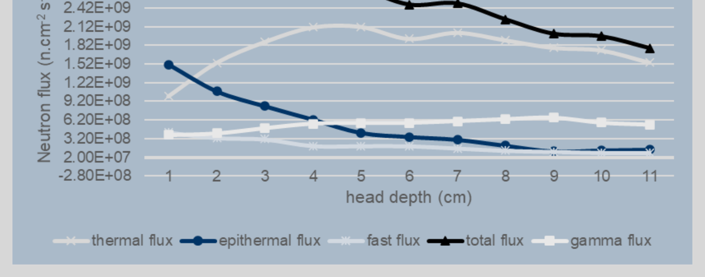

Figure (2): Neutron flux and gamma flux distributions along the head depth before ^{10}B injection.

The biological dose rate released to normal and tumor tissues is calculated at different ^{10}B concentration (10 – 50 ppm). Figure (3- a, b) show the results of biological dose at ^{10}B concentration 10 and 50 ppm. The results indicate that biological dose is increasing with ^{10}B concentration increase. The boron dose is the most effected component on the total biological dose is inside the tumor. Proton and gamma doses decrease along the head depth. The Healthy tissues beyond the tumor receive the lowest radiation dose. The lowest dose is at a health cells at skin surface, and at the skull due to high dense.

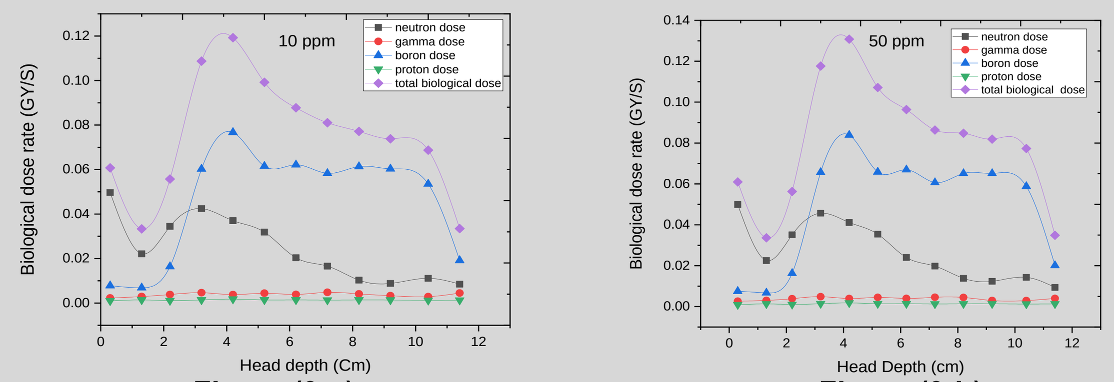

Figure (3-a) **Figure (3-b)**

Figure (3): The values of total biological dose rate and its components along the head depth for various injected ^{10}B concentrations.

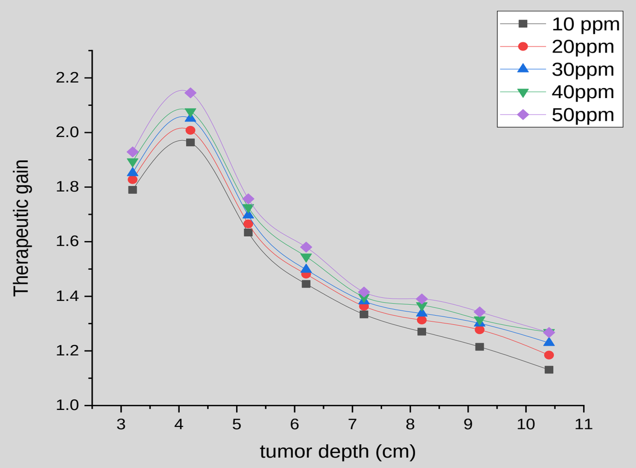

Figure (4): Therapeutic gain versus different head depths for various injected ^{10}B concentrations.

This figure shows the **therapeutic gain** (TG) for different ^{10}B concentrations (10-50 ppm) injected at the tumor cell. The results show that the therapeutic gain increases as the boron concentration increases at tumor cell.

CONCLUSION

1. The proposed BSA model geometry configuration gave a BNCT neutron beam characteristics are in compatible with the neutron beam criteria recommended by the IAEA. **– 2. The thermal ratio** founded may be more suitable to treat superficial tumors. **– 3. The proposed head model** illustrate that the higher thermal flux is in tumor cells, and epithermal and fast flux decreases along the head depth due to continuous slowing down inside the tumor cell tissues. **– 4. The biological dose** is increasing with ^{10}B concentration increase. And the total biological dose is mainly depend on the boron dose component. **– 5. The Healthy tissues** at the skin surface, skull and beyond the tumor receive the lowest radiation dose. **– 6. TG** may be used as a fast evaluation of the impact of varying ^{10}B concentrations on the therapeutic outcome, and treatment optimization.

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