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# A bi-tapered and air-gapped beam shaping assembly used for AB-BNCT

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ABSTRACT

The $^{7}$Li(p,n)$^{7}$Be reaction, which leads to a soft neutron field, is often chosen as the neutron producing reaction used for accelerator-based boron neutron capture therapy (AB-BNCT). This study aims to design a compact beam shaping assembly (BSA) and auxiliary system for a $^{7}$Li(p,n)$^{7}$Be reaction-based neutron source and to evaluate the relationship between the BSA design and the consequent neutron beam quality for further optimization.

In this study, five types of moderator shapes for the BSA model were designed. Both the in-air and in-phantom figures of merit were considered to evaluate the performance of the BSA designs. It was found that the BSA with a bi-tapered and air-gapped design could generate a high-intensity epithermal neutron beam, which could be used to treat deep-seated brain tumors within a reasonable time.

## 1. Introduction

In boron neutron capture therapy (BNCT), an epithermal neutron beam (0.5 eV $< E_n <$ 10 keV) is commonly used as a neutron source since the penetrability of the epithermal neutron is suitable for deep-seated tumors, and the induced normal tissue dose can be limited to the tissue tolerance. The $^{9}$Be(p,n)$^{9}$B and $^{7}$Li(p,n)$^{7}$Be reactions are commonly used as the neutron producing reaction for accelerator-based boron neutron capture therapy (AB-BNCT). Compared to the $^{9}$Be(p,n)$^{9}$B reaction, the $^{7}$Li(p,n)$^{7}$Be reaction can induce a softer neutron beam, which requires less moderation. Therefore, it is much easier to design a compact beam shaping assembly (BSA) and corresponding auxiliary systems when the $^{7}$Li(p,n)$^{7}$Be reaction is chosen as the neutron producing route for AB-BNCT.

From our preliminary study (Lee et al., 2014), the $^{7}$Li(p,n)$^{7}$Be reaction leads to a divergent neutron field. Fig. 1 shows the double differential neutron yield induced by the $^{7}$Li(p,n)$^{7}$Be reaction. As we can see from the figure, both the intensity and the energy of neutrons are anisotropic and forward peaked. To obtain a high-intensity epithermal neutron beam, it is essential to moderate the high energy neutrons emitted at the smaller angle while preserving the soft neutrons emitted at the larger angle as much as possible. We evaluated the characteristics and dosimetry performance of the neutron beams induced by proton beams with different incident angles, and a BSA model using noncollinear incident protons was designed in our preliminary study.

However, compared with the neutrons induced from a typical proton beam alignment, the neutron flux induced from a noncollinear proton beam is usually asymmetrical in the intensity and energy. Especially when the neutron distribution moves toward the outer part, away from the beam aperture, the asymmetry problem was more observable. However, the problem can be easily solved by adding extra shielding to suppress the neutron leakage. The protruding structure caused by additional shielding may cause patient positioning problems. In this study, as opposed to using the noncollinear incident proton beam, we focused on modifying the shape and the arrangement of the moderator, a part of the BSA's components. This was done to try to achieve the same goal, which is to efficiently moderate the neutrons induced from the $^{7}$Li(p,n)$^{7}$Be reaction based on the fact that these neutrons are divergently distributed.

## 2. Material and methods

### 2.1. Neutron producing unit

The melting point and thermal conductivity of lithium are 181 °C and 85 W(m-k)$^{-1}$, respectively. The physical properties make lithium an unattractive option for neutron producing. However, according to Bayanov et al., a good target design with appropriate support of cooling, a lithium target of 10-cm diameter is capable to sustain a power consumption of 25 kW without melting (Bayanov et al., 2006). In this study,

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a monodirectional proton beam with a current of 10 mA was used as the proton source. The protons that reacted with the lithium target were assumed to be at 2.5 MeV, an energy which can take advantage of the resonance peak at 2.25 MeV. There was an aluminum layer, with a thickness of 10 μm, attached to the target surface to prevent the lithium from being directly exposed to the air. Since we want to have 2.5 MeV protons reacting with the lithium target, the incident proton energy was assumed to be 2.75 MeV based on the stopping power of the aluminum. The lithium target was 98% $^{7}$Li enriched, with a thickness of 93.1 μm (Lee et al., 2000). Protons with energy lower than the threshold energy of the $^{7}$Li(p,n)$^{7}$Be reaction (1.88 MeV) will not contribute to the neutron production but instead will increase the photon contamination, since $^{7}$Li (p,p'γ) inelastic scattering will be induced when proton energy is higher than 0.5 MeV. To keep the number of induced photons as low as possible, the target thickness used in this study was just sufficient to brake the protons to the reaction threshold energy.

A 2 mm-thick copper sheet was used as the target backing. Protons that pass through the lithium target will die in the copper, and the heat produced from the $^{7}$Li(p,n)$^{7}$Be reaction will also be absorbed. A simple cooling system made of copper, tantalum, and water was also applied in our models. Fig. 2 shows the 2D and 3D view of the neutron producing unit.

### 2.2. Neutron intensity and quality evaluation

Both the in-air and in-phantom figures of merit were calculated to evaluate the neutron beam intensity and quality produced from different types of BSA. For the in-air figures of merit, five parameters retrieved from the IAEA-TECDOC-1223 report (IAEA, 2001) were used, and each one was suggested with a target value for designing the BSA. The tally segment for the Monte Carlo simulation was a 2-cm diameter circular plane and located at the center of the neutron beam exit surface. The energy range of epithermal neutron assumed in this study was 0.5 eV–10 keV. The neutron and photon kerma factors of ICRU 44 brain material were used to calculate the fast neutron and photon dose (Goorley et al., 2002 and Hubbell and Seltzer, 1995).

For the in-phantom figures of merit, we used the modified Snyder head phantom to perform the dosimetry calculation (Goorley et al., 2002). The tally segments were 93 tiny cuboids, with 2-mm thick and 16-mm side length, located at the central line of the phantom. The neutron and photon fluxes were tallied and multiplied by the kerma factors to obtain the boron, neutron and photon dose of each cuboid. Parameters including advantage depth (AD), advantage depth dose rate (ADDR), advantage ratio (AR), 30 w-Gy treatable depth (TD), irradiation time and tissue doses were used to evaluate the neutron quality (Lee et al., 2000). The $^{10}$B concentration was assumed as 18 ppm in blood. The parameters for the equivalent dose calculations are listed in Table 1 (Herrera, 2011).

### 2.3. Beam shaping assemblies

Five BSA models were shown in this study, and the main difference between each one is the shape and the alignment of the moderator. The typical moderator design for BSA is a simple cylindrical shape. Such a design was also the basic one in our study. Regarding the neutron energy degradation, $AlF_3$ was used as the moderator material, and a thin $^{6}$Li layer was added to absorb the thermal neutrons. The density of the $AlF_3$ moderator was assumed to be 2.78 g/cm$^3$, which is 90% of its theoretical density at room temperature. Around the moderator, we applied lead to reflect the neutrons to the central axis of the BSA. A 40 wt% lithium embedded polyethylene sheet was applied to the neutron beam aperture to deal with the leakage neutrons.

The thickness and diameter of the moderator were modeled from 1 to several tens of centimeters, however, only some particularly designs were shown due to the limited length. The reflector thickness was not optimized since the purpose of this study was the influence of moderator shape on neutron beam quality. As the fast neutrons react with the hydrogen in tissue through elastic scattering, the produced high-LET recoil protons result in large energy deposition in the skin and the shallow tissues. Such doses will limit the irradiation time and the tumor

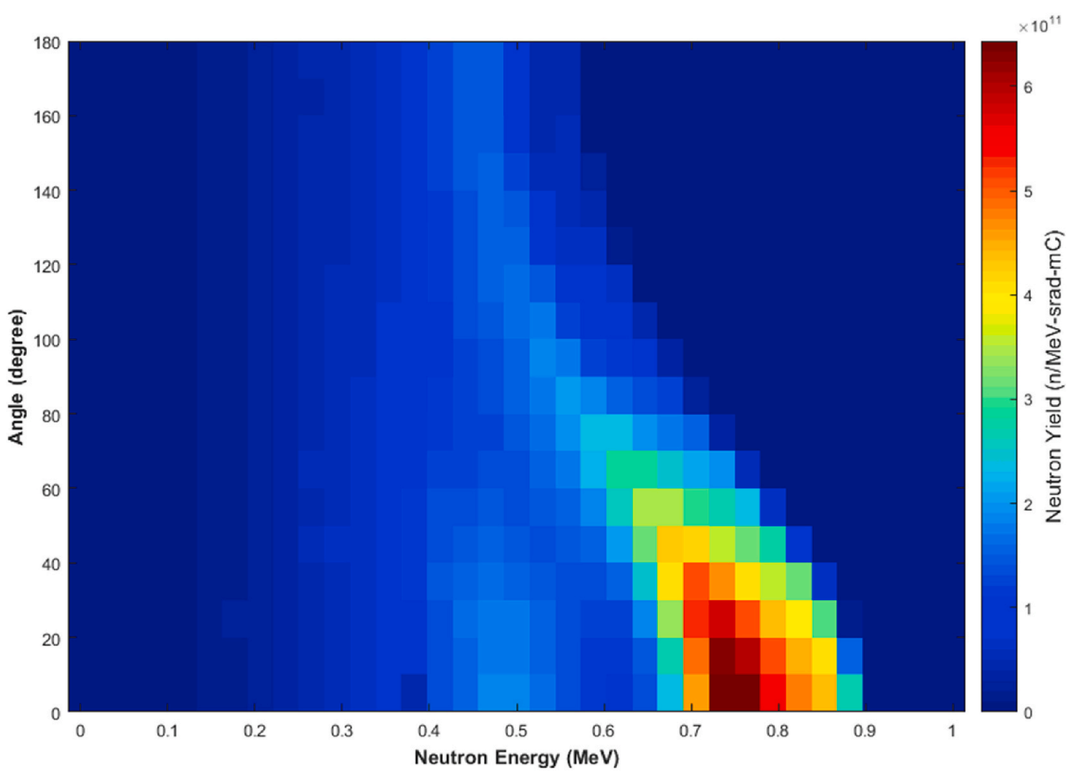


**Fig. 1.** Double differential neutron yield. The neutrons were produced from the reaction of 2.5 MeV protons and a 93.1 μm-thick lithium target.

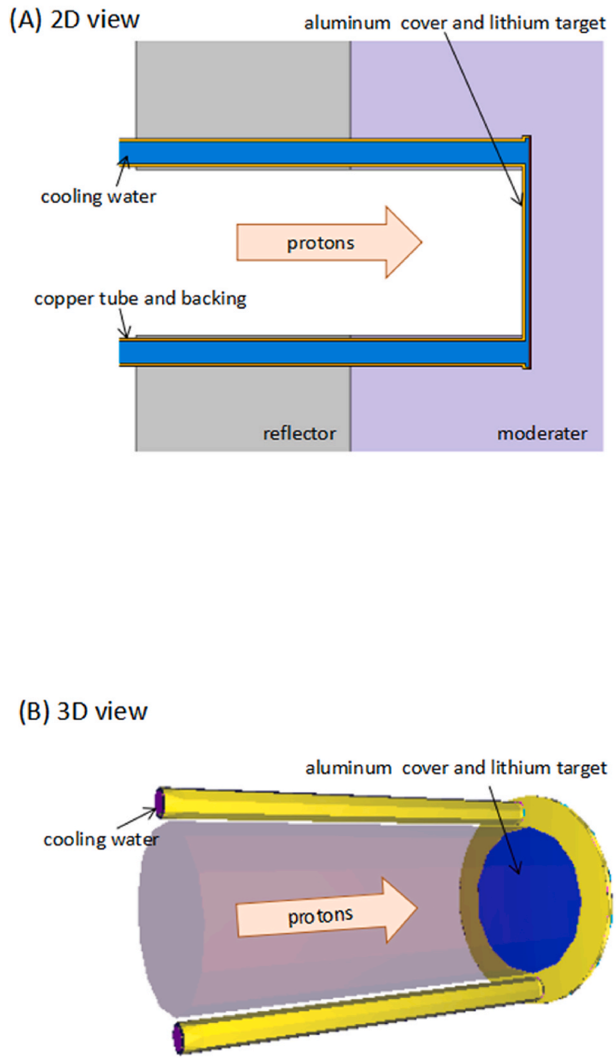


**Fig. 2.** (A) 2D view (B) 3D view of the neutron producing unit.

**Table 1**
Parameters used in dosimetry calculation.

| Tissue | RBE | | $^{10}$B-BPA CBE | T/N ratio |
|---|---|---|---|---|
| | Gamma-ray | Neutron | | |
| Brain | 1 | 3.2 | 1.3 | 1 |
| Skull | 1 | 3.2 | 0 | 0 |
| Skin | 1 | 3.2 | 2.5 | 1.5 |
| Tumor | 1 | 3.2 | 3.8 | 3.5 |

dose. Hence, the size of the $AlF_3$ moderator cylinder in the BSA was decided based on the size where the fast neutron contamination close to the target value suggested by IAEA. Based on the premise that the fast neutron contaminations were comparable and the biggest diameter of the moderators were fixed, a mono-tapered BSA and a bi-tapered BSA were designed. For the fourth model, we shrank the moderator by a small amount to create an air-gap between the moderator and the lead reflector. Further, to clarify whether either the size of the moderator or the additional air-gap contributed more to the production of epithermal neutrons, there was a fifth design in which the air-gap was filled with lead. That is, the fifth model could be considered a smaller version of the third one, the bi-tapered BSA without a gap. Fig. 3 shows the cylinder-shaped BSA design with the modified Snyder head phantom, and Fig. 4 shows the other four BSA models.

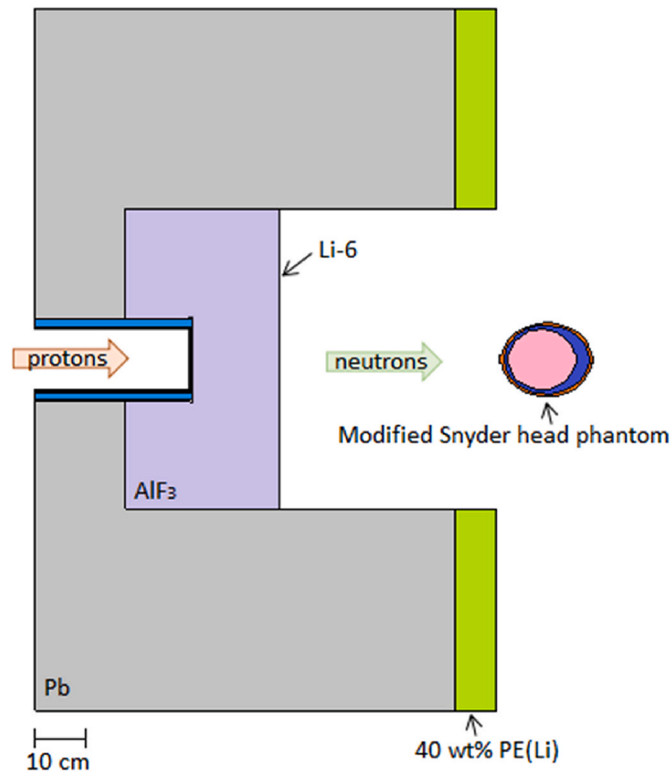


**Fig. 3.** Cylinder-shaped BSA with the modified Snyder head phantom.

## 3. Results and discussions

From our hundreds of simulations, the cylinder-shaped moderator with 45.5-cm thick and 60-cm diameter was selected in this paper, since its fast neutron contamination was closer to the IAEA recommendation than the others. The first three models were designed with different moderator sizes and shapes, but the induced fast neutron contaminations were comparable if the Monte Carlo calculation errors were taken into consideration. According to the calculation results, as shown in Table 2, the bi-tapered design can increase the beam intensity by 38% and 4% when compared to the typical cylinder and the mono-tapered BSA, respectively. Further, the photon contamination was also largely reduced. From the viewpoint of the in-air figures of merit, changing the moderator shape from a typical cylinder to a bi-tapered shape could effectively raise the epithermal neutron intensity. Furthermore, the moderator of the bi-tapered BSA was much lighter than that of the cylinder-shaped and the mono-tapered models.

When an air gap was integrated, the beam intensity was further raised by 8% of that in the bi-tapered model, and the photon contamination was decreased by 35%. Nevertheless, the fast neutron contamination also increased due to the absent moderator materials, which were replaced by the air gap. For the fifth BSA design, we filled the air gap applied in the fourth BSA model with the lead. From Table 2, the induced epithermal neutron fluxes from the bi-tapered BSA and the model with Pb-filling were approximately the same. However, the corresponding contamination showed no improvement with the application of the Pb-filling, that is, merely shrinking the moderator size of the bi-tapered model would not improve the neutron intensity and quality. The intensity increment of the fourth BSA model, the bi-tapered and air-gapped one, did not result from the smaller size of the moderator but the application of the air gap.

Table 3 shows the in-phantom figures of merit of all BSA models. In the tissue dose calculation, the 70 w-Gy maximum tumor dose was assumed as the irradiation endpoint. As we can see from the results, the normal brain and skin doses did not exceed the tolerance for all

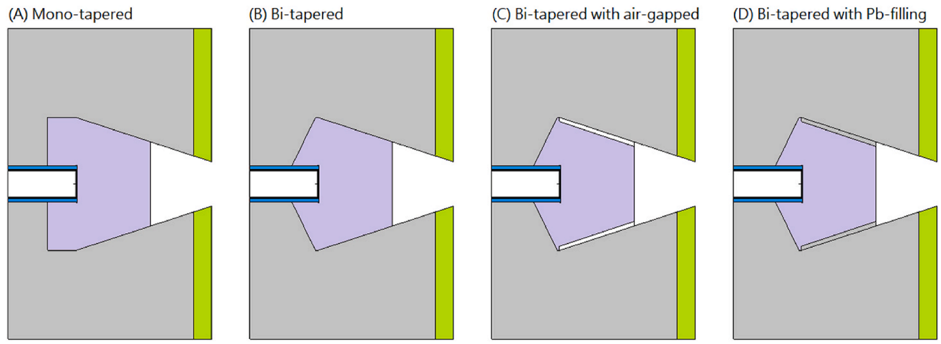


**Fig. 4.** Cross-sectional view of (A) Mono-tapered (B) Bi-tapered (C) Bi-tapered with air-gapped (D) Bi-tapered with Pb-filling BSA models.

**Table 2**
In-air figures of merit of neutrons produced from five BSA models.

| BSA models | | Figures of merit | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\phi_{epi.}$ [a] ($epi.n/cm^2s$) | $D_f/\phi_{epi.}$ ($Gy\ cm^2/epi.n$) | $D_r/\phi_{epi.}$ ($Gy\ cm^2/epi.\ n$) | $\phi_{ther.}/\phi_{epi.}$ | $J_{epi.}/\phi_{epi.}$ | Moderator weight[b] (kg) |
| | IAEA suggested value | >1.00E+9 | <2E-13 | <2E-13 | <0.05 | >0.70 | n/a |
| 1 | Cylinder | 0.82E+9 | 2.07E-13 | 2.40E-13 | 0.03 | 0.72 | 350 |
| 2 | Mono-tapered | 1.08E+9 | 1.97E-13 | 1.69E-13 | 0.03 | 0.73 | 270 |
| 3 | Bi-tapered | 1.12E+9 | 1.97E-13 | 1.46E-13 | 0.03 | 0.72 | 220 |
| 4 | Bi-tapered w/air-gap | 1.21E+9 | 2.40E-13 | 1.03E-13 | 0.02 | 0.72 | 190 |
| 5 | Bi-tapered w/Pb-filling | 1.12E+9 | 2.16E-13 | 1.40E-13 | 0.03 | 0.72 | 190 |

The standard errors of all parameters were <3%.
[a] The proton current was assumed to be 10 mA.
[b] The moderator weights were calculated round to the nearest ten.

**Table 3**
In-phantom figures of merit of neutrons produced from five BSA models. The 70 w-Gy maximum tumor dose was assumed to be the irradiation endpoint.

| BSA models | | Figures of merit | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | AD (cm) | ADDR (cGy/mA/min) | AR | 30 w-Gy TD (cm) | Irradiation time (mins) | Max. Skin dose (w-Gy) | Max. Normal brain dose (w-Gy) |
| | target value | >10.0 | n/a | n/a | >7.0 | <30 | <11.0 | <12.5 |
| 1 | Cylinder | 11.5 | 3.21 | 4.47 | 8.1 | 36.9 | 10.7 | 11.9 |
| 2 | Mono-tapered | 10.7 | 3.67 | 3.56 | 7.4 | 31.8 | 9.2 | 10.2 |
| 3 | Bi-tapered | 10.8 | 3.81 | 3.72 | 7.4 | 30.4 | 8.8 | 9.8 |
| 4 | Bi-tapered w/air-gap | 11.2 | 4.13 | 4.12 | 7.5 | 28.2 | 8.2 | 9.1 |
| 5 | Bi-tapered w/Pb-filling | 10.7 | 3.84 | 3.68 | 7.4 | 30.3 | 8.8 | 9.7 |

The standard errors of all parameters were <3%.

irradiation scenarios. Despite the fact that the treatable depth was not the deepest when the BSA model was changed from the cylinder to the other designs, the 30 w-Gy TD and the AD parameters in all scenarios were still beyond 7.0 cm and 10.0 cm in phantom, respectively. This result indicated the great penetrability of the neutron beams.

The bi-tapered and air-gapped design could provide the highest tumor dose rate. In other words, with the use of the neutron beam produced from the bi-tapered and air-gapped BSA, each therapy could be finished within the shortest amount of time. Further, the corresponding normal brain and skin doses were relatively low when compared with the other BSA models. The tumor dose could be much higher in the bi-tapered and air-gapped case if the normal tissue tolerance was assumed to be the irradiation endpoint.

As a result, the beam shaping assembly with a bi-tapered and air-gapped design could generate a high-intensity epithermal neutron beam, increasing 21% beyond the IAEA recommendation. Additionally, the dosimetric performance in the modified Snyder head phantom shows the treatment efficacy and demonstrates that deep-seated brain tumors can be treated in a reasonable amount of time.

## 4. Conclusions

From the results of this study, the BSA with the bi-tapered and air-gapped design could produce a high intensity epithermal neutron beam with good penetrability. To induce a 70 w-Gy maximum tumor dose, the required irradiation time is less than half an hour when using a 2.75 MeV, a 10 mA proton beam as the source to react with the lithium target unit. Further, the 30 w-Gy treatable depth could be deeper than 7.0 cm, which would satisfy almost all brain tumor treatments. Additionally, the moderator size of the bi-tapered and air-gapped BSA was the smallest in all the models, which makes it more possible to manufacture a compact BSA.

By increasing the epithermal neutron intensity, the irradiation time could be shortened. It would benefit the patient positioning during the treatment and would help to effectively use the limited residence time of $^{10}$B-enriched complex. Further, the proton current would have less demand with a fixed irradiation time, and vice versa; thus, the lifetime of the lithium target could also be prolonged. This would result in reducing the amount of radiation waste produced and save on equipment operating expenses.

This study attempted to provide an idea of efficiently moderating the divergent neutrons produced from the $^{7}$Li(p,n)$^{7}$Be reaction by modifying the shape and the arrangement of the moderator. Other items of concern, such as the reflector, the thermal neutron absorber, the neutron leakage filter, the radiation shield and the materials of each BSA component, were not optimized. The Further optimization should be executed to create a superior epithermal neutron beam for AB-BNCT.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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