Electronic Physician (ISSN: 2008-5842) http://www.ephysician.ir
June 2017, Volume: 9, Issue: 6, Pages: 4590-4596, DOI: http://dx.doi.org/10.19082/4590

Optimization of the photoneutron target geometry for e-accelerator based BNCT

Nahid Chegeni[1], Saleh Boveiry Pur[2], Sasan Razmjoo[3], Seydeh Khadijed Hoseini[2]

[1] Ph.D. of Medical Physics, Assistant Professor, Department of Medical Physics, Faculty of Medicine, Ahvaz Jundishapur University of Medical Sciences: Ahvaz, Iran
[2] M.Sc. of Medical Physics, Department of Medical Physics, Faculty of Medicine, Ahvaz Jundishapur University of Medical Sciences: Ahvaz, Iran
[3] M.D. of Radiotherapy and Oncology, Assistant Professor, Department of Radiotherapy and Oncology, Golestan Hospital, Faculty of Medicine, Ahvaz Jundishapur University of Medical Sciences: Ahvaz, Iran

Type of article: Original

Abstract

Background and aim: Today, electron accelerators are taken into consideration as photoneutron sources. Therefore, for maximum production of epithermal neutron flux, designing a photoneutron target is of significant importance. In this paper, the effect of thickness and geometric shape of a photoneutron target on neutron output were investigated.

Methods: In this study, a pencil photon source with 13, 15, 18, 20 and 25 MeV energies and a diameter of 2 mm was investigated using Monte Carlo simulation method using MCNP code. To optimize the design of the photoneutron target, the tungsten target with various geometries and thicknesses was investigated.

Results: The maximum neutron flux produced for all target geometries and thicknesses occurred at neutron energy peak of around 0.46 MeV. As the thickness increased to 2 cm, neutron flux increased and then a decreasing trend was observed. For various geometrical shapes, the determining factor in photoneutron output was the effective target thickness in the photon interaction path that increased by the increase in the area of interaction. Another factor was the angle of the photon's incidence with the target surface that resulted in a significant decrease in photoneutron output in cone-shaped targets

Conclusion: Three factors including the total neutron flux, neutrons energy spectrum, and convergence of neutrons plays an important role in the selection of geometry and shape of the target that should be investigated considering beam shaping assembly (BSA) shape.

Keywords: Neutron Therapy; Electron Accelerator; Photoneutron Target

1. Introduction

Today, it is confirmed that some cancers can be treated using Boron Neutron Capture Therapy (BNCT). The advantage of BNCT is the secondary particles from the decay with high linear energy transfer (LET) and therefore, they pass a short distance into the tissue and deposit their energy in a small area. This leads to the increase in direct effects of radiation and reduces damage to the normal tissue, and compared to photon radiation therapy, it has a higher dose in the tumor region (1). Not only is BNCT safe and maintains the normal tissue, but also, it removes indistinguishable cancer cells (2). The main problem of BNCT is related to the difficulty in epithermal neutron production with an appropriate flux for therapy (3). One of the most practical sources appropriate for producing epithermal neutron for BNCT is nuclear reactors. However, due to their high costs and dimensions to be installed and operated in hospitals, using these sources is limited to few countries. In search for new sources, researchers have proposed using cyclotron accelerators, indirect production of neutrons and radioactive sources neutron emitters, each of which has its own advantages and disadvantages (4-9). Though, in developing countries, radiotherapy departments are often equipped with electron linear accelerators and some work is conducted to utilize this accelerator to produce epithermal neutrons

---

Corresponding author:
Assistant Professor Dr Nahid Chegeni, Department of Medical Physics, Faculty of Medicine, Ahvaz Jundishapur University of Medical Sciences: Ahvaz, Iran. Tel: +98.916 353 4022, Email: chegenin@gmail.com

Received: September 09, 2016, Accepted: December 22, 2016, Published: June 2017
iThenticate screening: December 08, 2016, English editing: June 10, 2017, Quality control: June 12, 2017

(10-15). The benefits of electron linear accelerators are their low cost, small dimensions, high safety, and high social acceptability that make them a good choice to be utilized in hospitals (16). The basis in these neutron sources is such that first, electrons are accelerated to energy of about MeV and after colliding a target made of heavy metals, Bremsstrahlung radiation occurs and Mega Voltage x-rays are produced. By putting materials with high atomic number on the path of high-energy photons, the possibility of reactions (γ, n) is provided and a neutron is produced. In this method, neutron production starts when the energy of electrons is about 10MeV (17). Much research is conducted on the type and thickness of the photoneutron target on various materials including W, U, D_2O, Pb, and BeD_2, each of which has its own advantages and limitations (12, 14, 18, 19). For example, Uranium (U) possesses the highest photoneutron flux; however, its neutron flux energy spectrum is higher than others, and the average energy of neutrons resulted from it is in the range of fast neutrons. The other disadvantages are its high cost, inaccessibility, patient's fear, and the need to have necessary licenses to work with uranium (18). After U, tungsten (W) has the highest neutron flux relative to other materials and due to its advantages such as easy access, reasonable price and lack of toxicity (similar to Pb), it has been selected in most studies as the photoneutron target (14, 18, 20, 21). In this study, the effect of thickness, geometry, and orientation of photoneutron target on neutron flux and neutron energy flux and the convergence of the neutron output is investigated using MCNPX simulation code, then they are compared and the optimum target is selected.

2. Material and Methods

Using MCNPX6.2 code, simulation of geometry and calculation of output neutron energy flux, neutron flux and drawing results of calculations were conducted using Excel software. A pencil beam with diameter of 2mm and single energy was simulated with 13, 15, 18, 20 and 25 MeV energies using MCNP code. The number of particles used in simulation was 6×10^8 and acceptable relative error was less than 1%. To reduce the program runtime and measurement error, variance reduction methods used in MCNP code were employed, including photon and electron energy cut (Pcut=0.1Mev and Ecut=0.7 Mev) as well as splitting and Russian roulette for both geometry and energy. Due to low thermal and epithermal neutron fluxes relative to fast neutrons, weight window energies were utilized. As the target material for interaction (γ, n), tungsten was selected due to its important characteristics such as high atomic number (Z=74), high density (ρ=19.25 g/cm^3), high thermal tolerance (melting point of 3422 °C) and high thermal transfer. Using photons with energies of about 12MeV to 18MeV, increases output neutron flux due to the photonuclear process of giant dipole resonance (γ,xn) (Figure 1) (22).

To select the optimum energy for photons hitting the target, single energy photon source was employed with 13, 15, 18, 20, and 25MeV energies. Then, by determining the appropriate energy of radiation photon, the rest of the simulations were conducted with that energy. A disk-shaped tungsten target with a diameter of 8cm and thicknesses of 1, 1.5, 1.8, 2, 2.3, 2.5, and 3cm was investigated. All measurements were conducted in a 10cm distance from the photoneutron target (Figure 2). To reduce the simulation runtime, the entire space was filled with vacuum. To investigate the convergence of neutrons (move forward), the ratio of neutron flux to the total number of neutrons passing through the surface was used (23). Various geometries were employed to calculate and compare the efficiency of neutron flux production as well as convergence of the neutron output (Figure 3).

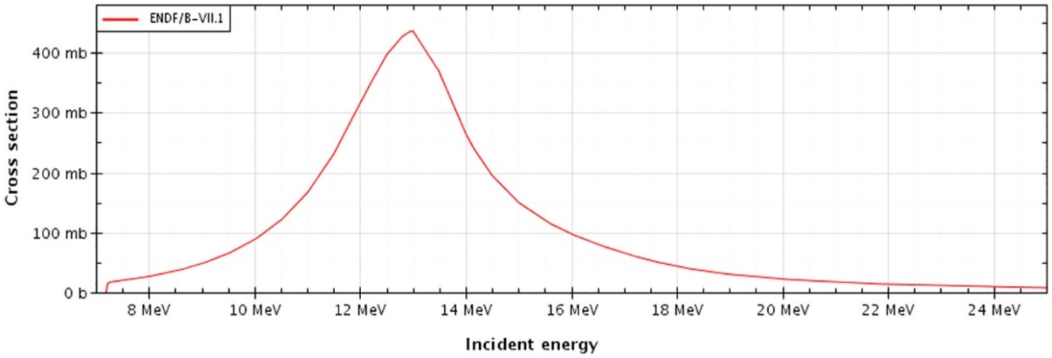

Figure 1. Photoneutron interaction cross sections of (γ, n) for Tungsten (22)

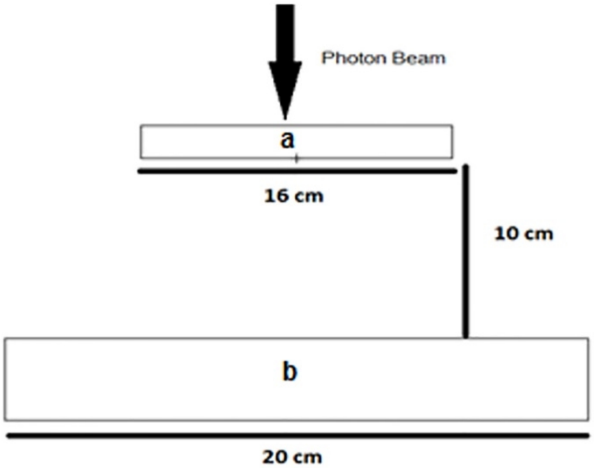

Figure 2. Photoneutron target (a) which produces neutron after colliding photons and the detector volume in simulation (b).

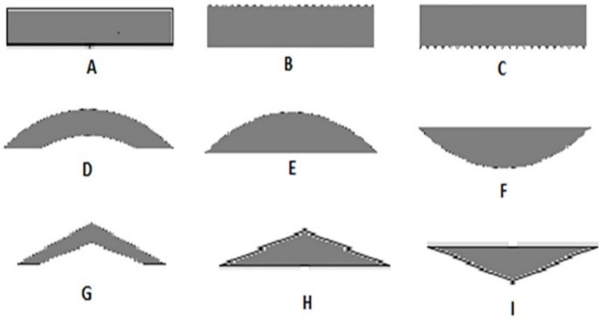

Figure 3. Photoneutron targets with cross-section 8cm radius and geometric shape of A) a disk with 2cm thickness, B) a disk with several hemisphere holes (2 mm radius) on the upper surface, C) a disk with several hemisphere holes (2mm radius) on the lower surface, D) a spherical shell with a 2cm thickness, E) a spherical slice with maximum thickness 2 cm, F) Figure E rotated 180°, G) a cone shell with 2cm thickness, H) a cone with 2 cm height, I) Figure H rotated 180°

3. Results

To assess the relation of neutron flux and photon energy produced via photonuclear interaction, photons with different energies were employed with a 2-cm tungsten target previously proposed by Rahmani (18). According to Figure 4, results of calculations show that for all radiation photon energies, the highest neutron flux was produced in 0.46MeV energy and this is the maximum value for 15 MeV energy. As can be seen in Figure 4, first, the produced neutron flux increases by the increase in energy of collision photon and then a decreasing trend is observed. To study the effect of the thickness of the tungsten target on efficiency of neutron flux production, the tungsten disk was used with various diameters. According to Figure 5, as the thickness increased from 1cm to 2cm, neutron flux increased and then a decreasing trend was observed by increase in thickness. However, the highest efficiency is still observed in 0.46 MeV energy for all thicknesses. In the next step, the effect of geometrical shape and the effective area of the incident photon on neutron flux, energy flux and the convergence of neutron output were investigated (Figure 6). The highest output flux is related to target D.

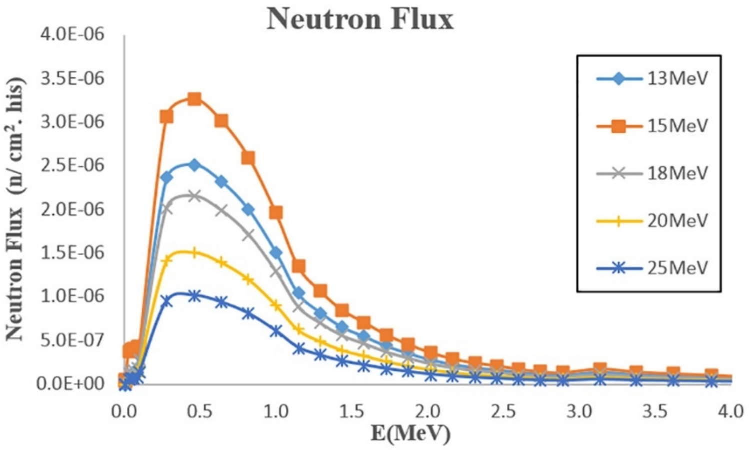

Figure 4. Neutron flux for different photon-energy beam in 2cm tungsten layer.

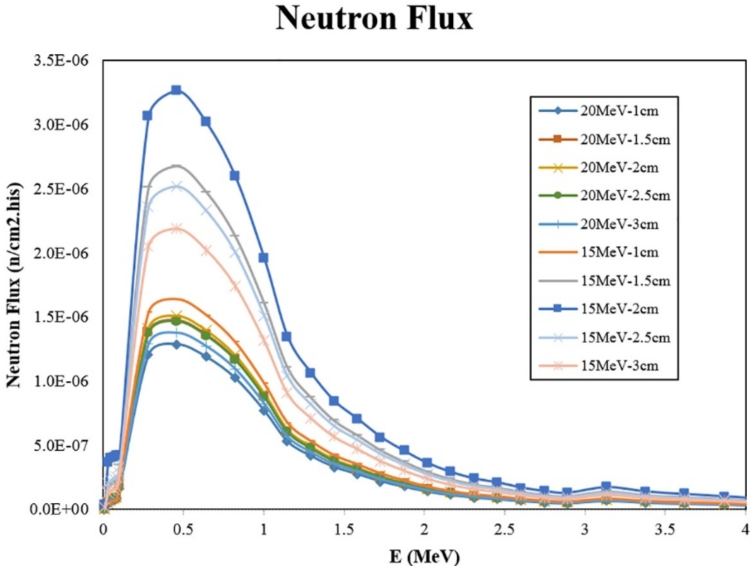

Figure 5. Neutron flux from a tungsten disk with different thicknesses and photon beam with energy 15, 20MeV.

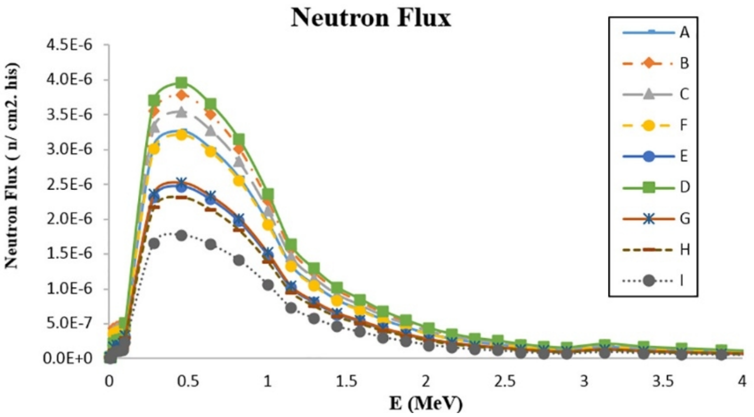

Figure 6. Neutron flux from the target with different shapes irradiated by photon 15MeV.

4. Discussion

Today, cyclotrons are employed for proton acceleration, and then by colliding ^{7}Li, a high-efficiency neutron is produced according to ^{7}Li (p,n), ^{7}Be interaction. However, since in developing countries it is not possible to use cyclotrons in general, linear accelerators are an acceptable source to generate clinical neutrons. Therefore, for maximum production of epithermal neutron flux, designing the incident target of mega voltage photons to produce neutrons is of significant importance. In this paper, the effect of thickness and the geometric shape of the photoneutron converter have been investigated. Important physical quantities related to IAEA standard to select photoneutron source are total neutron flux (φ) and the ratio of neutron flux to neutron current (that shows convergence) (22). As neutron flux increases, the healing time is reduced and as the convergence of neutron output increases, unwanted exposure of normal tissue is prevented and there is a better possibility for patient positioning along the main axis of the beam. Other physical quantities, including the energy flux (ψ) and mean energy ($\bar{E}$) of total neutrons passing the measured area show the quality of neutron beam and they have a special importance in designing BSA. Considering data related to photoneutron interaction cross section for tungsten (Figure 1), the highest neutron flux was expected to occur for 13MeV photon, and this is while calculations show that the highest produced neutron flux occurs for about 15MeV photon (Figure 4). As the energy of incident photon increases from 13MeV to 15MeV, the produced flux increases for 30%, and this is while the energy of incident photon increases to 18MeV, the produced flux reduces for about 34% and this decreasing trend is observed as the energy increases. One of the reasons to justify this trend is increased penetration of 15MeV photon relative to 13MeV photon and the fact that as energy increases, the significant decrease in photonuclear interaction cross section has resulted in the drop of neutron flux. This is while in previous studies only one increasing trend is reported (18, 20). The reason behind this discrepancy is the difference in the type of falling beam on the tungsten target, and in those studies, the electron beam is employed. To assess the effect of penetration of photon on produced neutron flux, calculations were conducted using a tungsten target with various thicknesses and photons with 15 and 20MeV energies. For 15MeV energy and the increase of thickness, the produced neutron flux shows an increasing trend that suggests the possible increase of photoneutron interaction and the highest neutron is produced for the thickness of 2cm. For over 2cm thicknesses, a deceasing trend was observed due to the attenuation of neutron and photon flux. As can be seen in Figure 5, such a trend is repeated for 20MeV energy; however, the effect of thickness on produced neutron flux is less, which could be the result of slower decreasing trend of the photoneutron interaction cross section around this energy. For a target with various geometrical shapes, as the incident surface of photon increases without sensible change of thickness, targets B and C (with relatively twice input and output surface) show a 17% and 10% increase respectively. In addition, target D has the effective thickness of 2cm. However, since the effective surface of incident photons has increased, it contains the highest output neutron flux. Concerning targets E and F, with regard to the decrease of effective thickness, they show a reduction on 38% and 19% relative to D. In other words, using a hemisphere such that the photon hitting a flat surface is more efficient to produce neutrons, as Torabi has employed this geometry (14). Regarding cone-shaped targets, target G has a higher output flux relative to targets H and I due to having thickness that is more effective. However, as can be seen in Figure 6, it has a lower flux compared to other geometries. Considering the larger incident surface of target G relative to target A and similar thicknesses, this may be due to the change in the angle of incidence of the photon colliding with the target. Previous studies have not investigated the effect of the shape of photoneutron converter. According to Table 1, maximum total neutron flux produced, resulted from the collision of photon with 15MeV energy with target D and maximum total energy flux occurred are related to targets A, B, and C which are disk-shaped. This is while the minimum and maximum mean energy of passing neutrons are related to targets D and I respectively. Therefore, considering the neutron energy limit required in therapy, the shape of the photonuclear converter could be selected. According to IAEA, the acceptable convergence for neutron output in BNCT therapy is at least 0.7. The convergence of neutron output increases by an increase in mean energy (E_n) and this shows that energetic neutrons move forward more and show less scattering. Therefore, target D is of least convergence and the highest convergence is related to target I. Finally, to select the photoneutron target, all three factors of neutron flux, energy spectrum, and convergence of neutron output should be considered.

Table 1. The total neutron flux (n.cm^{-2}.his^{-1}) n_φ, average energy per neutron E_n (MeV/n), the total energy flux, and the convergence of neutrons ($\Phi_{n,\ total} / I_{n,\ total}$) for various target shapes irradiated by photon energy 15MeV.

Shape No	A	B	I	H	G	F	E	D	C
$\Phi_{n,total}\times 10^{-5}$ (n/cm^2.his) (relative error)	2.37 0.05%)	2.75 (0.06%)	1.23 (0.48%)	1.62 (0.26%)	1.98 (0.10%)	1.51 (0.21%)	1.75 (0.19%)	2.77 (0.07%)	2.57 (0.05%)
$\Psi_{n,total}\times 10^{-5}$ (MeV/cm^2.his) (relative error)	1.62 (0.05%)	1.63 (0.05%)	1.43 (0.05%)	1.43 (0.05%)	1.58 (0.05%)	1.49 (0.05%)	1.49 0.05%)	1.60 (0.05%)	1.63 (0.05%)
$\bar{E}_n$ (MeV/n)	0.68	0.59	1.16	0.88	0.79	0.98	0.85	0.57	0.63
$\Phi_{n,total} / I_{n,total}$	0.66	0.57	0.77	0.73	0.67	0.77	0.72	0.53	0.61

5. Conclusions

In this study, it was shown that the thickness and geometry of photoneutron source could have a significant effect on flux, average energy, and the convergence of the neutron output. On the other hand, the energy spectrum of photon radiated on photonuclear converter can affect the convergence and output neutron flux. Thus, it is suggested to use an electron accelerator instead of a single energy photon beam. Therefore, considering the neutron energy limit required in BNCT and photon source therapy, the appropriate photoneutron converter geometry could be selected.

Acknowledgments:

This study was extracted from a master thesis of Medical Physics approved by Ahvaz Jundishapur University of Medical Sciences (U-94074). Hereby, the Research Deputy of Ahvaz Jundishapur University of Medical Sciences and Medical Physics Department are appreciated.

Conflict of Interest:

There is no conflict of interest to be declared.

Authors' contributions:

All authors contributed to this project and article equally. All authors read and approved the final manuscript.

References:

1) Hall EJ, Giaccia AJ. Radiobiology for the Radiologist: Lippincott Williams & Wilkins; 2006.
2) Slatkin DN. A history of boron neutron capture therapy of brain tumours. Postulation of a brain radiation dose tolerance limit. Brain. 1991; 114(Pt 4): 1609-29. doi: 10.1093/brain/114.4.1609. PMID: 1884169.
3) Bisceglie E, Colangelo P, Colonna N, Santorelli P, Variale V. On the optimal energy of epithermal neutron beams for BNCT. Phys Med Biol. 2000; 45(1): 49-58. doi: 10.1088/0031-9155/45/1/304. PMID: 10661582.
4) Allen DA, Beynon TD. A design study for an accelerator-based epithermal neutron beam for BNCT. Physics in medicine and biology. 1995; 40(5): 807-21. doi: 10.1088/0031-9155/40/5/007. PMID: 7652009.
5) Blue TE, Yanch JC. Accelerator-based epithermal neutron sources for boron neutron capture therapy of brain tumors. J Neurooncol. 2003; 62(1-2): 19-31. doi: 10.1023/A:1023247222043. PMID: 12749700.
6) Green S. Developments in accelerator based boron neutron capture therapy. Radiation Physics and Chemistry. 1998; 51(4-6): 561-9. doi: 10.1016/S0969-806X(97)00203-X.
7) Kobayashi H, Kurihara T, Matsumoto H, Yoshioka M, Matsumoto N, Kumada H, et al. Construction of a BNCT facility using an 8-MeV high power proton linac in Ibaraki.
8) Kononov OE, Kononov VN, Bokhovko MV, Korobeynikov VV, Soloviev AN, Sysoev AS, et al. Optimization of an accelerator-based epithermal neutron source for neutron capture therapy. Appl Radiat Isot. 2004; 61(5): 1009-13. doi: 10.1016/j.apradiso.2004.05.028. PMID: 15308184.
9) Floberg J. The physics of boron neutron capture therapy: an emerging and innovative treatment for glioblastoma and melanoma. Physics and Astronomy Comps Papers. 2005.
10) Bevilacqua R, Giannini G, Calligaris F, Fontanarosa D, Longo F, Scian G, et al. PhoNeS: A novel approach to BNCT with conventional radiotherapy accelerators. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2007; 572(1): 231-2. doi: 10.1016/j.nima.2006.10.290.
11) Ludewigt B, Bleuel D, Chu W, Donahue R, Kwan J, Leung K, et al. Clinical requirements and accelerator concepts for BNCT. IEEE. 1997. doi: 10.1109/pac.1997.753418.
12) Naseri A, Mesbahi A. A review on photoneutrons characteristics in radiation therapy with high-energy photon beams. Reports of Practical Oncology & Radiotherapy. 2010; 15(5): 138-44. doi: 10.1016/j.rpor.2010.08.003. PMID: 24376940, PMCID: PMC3863143.
13) Nigg D, Mitchell H, Harker Y. Computational and Experimental Studies of an Electron Accelerator Based Epithermal Photoneutron Source Facility for Boron Neutron Capture Therapy. INEL BNCT Research Program Annual Report 1995. 1996: 27.
14) Torabi F, Masoudi SF, Rahmani F, Rasouli FS. BSA optimization and dosimetric assessment for an electron linac based BNCT of deep - seated brain tumors. Journal of Radioanalytical and Nuclear Chemistry. 2014; 300(3): 1167-74. doi: 10.1007/s10967-014-3087-0.
15) Salehi D, Sardari D, Jozani MS. Characteristics of a heavy water photoneutron source in boron neutron capture therapy. Chinese Physics C. 2013; 37(7): 078201. doi: 10.1088/1674-1137/37/7/078201.

16) Quintieri L, Bedogni R, Buonomo B, De Giorgi M, Chiti M, Esposito A, et al. A Photoneutron source at the Daϕne Beam Test Facility of the INFN National Laboratories in Frascati: design and first experimental results. Physics Procedia. 2012; 26: 249-60. doi: 10.1016/j.phpro.2012.03.033.
17) McGinley PH, Butker EK. Evaluation of neutron dose equivalent levels at the maze entrance of medical accelerator treatment rooms. Medical physics. 1991; 18(2): 279-81. doi: 10.1118/1.596713. PMID: 2046615.
18) Rahmani F, Shahriari M. Hybrid photoneutron source optimization for electron accelerator-based BNCT. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2010; 618(1-3, 1-21): 48-53. doi: 10.1016/j.nima.2010.02.268.
19) Huang WL, Li QF, Lin YZ. Calculation of photoneutrons produced in the targets of electron linear accelerators for radiography and radiotherapy applications. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2005; 229(3-4): 339-47. doi: 10.1016/j.nimb.2004.12.117.
20) Giannini G, Borla O, Bevilacqua R, Zanini A. Photoneutron source for in-hospital BNCT treatment: feasibility study. Proceedings of the 12th International Congress on Neutron Capture Therapy Takamatsu, Kagawa, Japan; 2006.
21) Jallu F, Lyoussi A, Payan E, Recroix H, Mariani A, Nurdin G, et al. Photoneutron production in tungsten, praseodymium, copper and beryllium by using high energy electron linear accelerator. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 1999; 155(4): 373-81. doi: 10.1016/S0168-583X(99)00487-5.
22) Waters LS. MCNPX user’s manual. Los Alamos National Laboratory. 2002.
23) Followill DS, Stovall MS, Kry SF, Ibbott GS. Neutron source strength measurements for Varian, Siemens, Elekta, and General Electric linear accelerators. J Appl Clin Med Phys. 2003; 4(3): 189-94. doi: 10.1120/1.1571671. PMID: 12841788.
24) Soppera N, Bossant M, Dupont E. Janis 4: An improved version of the nea java-based nuclear data information system. Nuclear Data Sheets. 2014; 120: 294-6. doi: 10.1016/j.nds.2014.07.071.
25) Coderre J. Current status of neutron capture therapy. IAEA-TECDOC-1223. IAEA, 2001.