ORIGINAL ARTICLE

Investigating the Possibility of Using Metamaterial as a Neutron Shield in BNCT Treatment to Reduce the Dose of Secondary Particles and Radioactive Elements Produced in Brain Tumor

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Abstract

Purpose: In this research, using the Geant4 software toolbox and metamaterials as a neutron shield, it was tried to introduce the proper metamaterial for this matter.

Materials and Methods: BNCT treatment is one of the most significant approaches used to treat brain tumors. The neutron source that is the main part of the BNCT method is produced by protons irradiation of ^{7}Li converter. The brain tumor tissue, which contains a high concentration of ^{10}B, is exposed to thermal neutron energy that is moderated by shield material. The dose of alpha particles that produced by the neutron decay of ^{10}B in tumor tissue can be calculated by changing the metamaterial thickness. The best thickness of metamaterial for minimizing the radioactive elements production in brain tumor is calculated using the Geant4 toolkit.

Results: WC metamaterial with 10 cm thickness is suitable for neutron moderation. The secondary elements produced in brain tumors is less than other thickness that is calculated by taking into account the alpha spectrum in tumor tissue. The alpha spectrum was calculated by the interaction of neutron spectrum released by the WC metamaterial.

Conclusion: The dose of alpha and secondary particles was obtained by the calculation of numbers and energy of these particles in brain tumors. The number of radioactive elements produced in the tumor tissue, as well as the most effective thickness of proper metamaterial to reduce the dose of secondary particles indicated that the WC metamaterial with a thickness of 17 cm is the best material for reducing radiation of neutron source that is produced by 35 MeV proton irradiation of ^{7}Li neutron converter.

Keywords: Boron Neutron Capture Therapy; Geant4 Toolkit; Metamaterial; Brain Tumor; Dosimetry; Proton.

DOI:

1. Introduction

Humans are made up of trillions of cells that typically grow and divide as needed throughout your life. When cells become abnormal or age, they usually die. Cancer starts when something goes wrong in this process, cells keep making new cells, and old or abnormal cells don't die when they should [1].Cancer can be successfully treated in many people. In fact, more people than ever before are living full lives after cancer treatment [2]. Cancer is more than just a disease. There are many types of cancer. Cancer can occur anywhere in the body and is named after the site where it forms. For example, breast cancer that starts in the breast is called breast cancer even if it has spread (metastasized) to other parts of the body [3]. There are 2 major classes of cancer: a) Blood cancers are cancers of blood cells such as leukemia, lymphoma, and multiple myeloma [4]. b) Solid tumor cancers are cancers of other organs and tissues of the body. The most common solid tumors are breast, prostate, lung, colon cancer, and brain tumors [5]. A tumor is a lump or growth. Some lumps are cancerous, but many are not [6]. Nodules that are not cancerous are called benign. Cancerous nodules are called malignant [7]. The difference between cancers is that they can spread to other parts of the body [8]. In this study, brain tumor is examined. Intracranial tumors have an incidence of 10-20 per 100,000 and account for ~ 2% of deaths in Western countries [9]. In adults, half of brain tumors are primary and the rest are metastatic. Primary brain tumors have a bimodal distribution, with a small peak early in childhood at 5-9 years and a much higher peak at 60-69 years. Primary brain tumors are the second most common cancer in children under the age of 15 and the third leading cause of cancer-related deaths in adults under the age of 34, but most of these tumors occur after age 50 [10]. Brain tumors are common and general practitioners should have a basic knowledge of their diagnosis and treatment. The most common brain tumors are intracranial metastases from systemic cancers, meningioma and glioma, especially glioblastoma [11]. Metastases to the central nervous system can occur anywhere along the nerve axis and require complex multidisciplinary management, including neurosurgery, radiation oncology, and medical oncology [12]. Meningiomas are tumors of the meninges, usually benign, often treated by surgical resection, with radiotherapy and chemotherapy reserved for high-risk or refractory diseases [13]. Glioblastoma is the most common and aggressive primary malignant brain tumor with limited response to standard combination chemoradiotherapy. A new classification of gliomas relies on molecular features and histology to arrive at an integrated diagnosis that more accurately captures the prognosis. Among these, one of the treatment methods is the Boron Neutron Capture Therapy (BNCT) method [14].

The BNCT is based on the nuclear reaction that occurs when boron-10 is bombarded with low-energy thermal neutrons to produce alpha particles and rebounding lithium-7 nuclei [15]. High-grade astrocytomas, glioblastoma multiforme, and metastatic brain tumors constitute the major groups of neoplasms for which there are no effective therapies. There is growing interest in using BNCT in combination with surgery to treat patients with primary and possibly metastatic brain tumors [14]. The current review of BNCT, which is selective rather than comprehensive, addresses radiobiological considerations, the development of tumor-localized boron compounds, neutron sources, and clinical studies. The main points covered in this review can be summarized as follows. For BNCT to be successful, a large number of 10B atoms must be localized on or preferably within the tumor cell. To sustain the lethal ^{10}B (n,a) ^{7}Li reaction, a sufficient number of thermal neutrons must reach the ^{10}B atom and be absorbed or trapped. It addresses two main questions. First, how can such a large number of ^{10}B atoms be selectively delivered to cancer cells? Two boron compounds, Borocaptate Sodium (BSH) and Boronophenylalanine (BPA), are currently in clinical use. and many new delivery systems are being investigated. Second, how can neutrons of such high fluence (n.cm^{-2}) be delivered to the tumor? Currently, nuclear reactors are the only neutron sources for BNCT. Fission processes in the core produce a mixture of low-energy thermal and epithermal neutrons, fast or high-energy (>10,000 eV) neutrons, and gamma rays. Thermal neutrons are used clinically in Japan to treat patients with brain tumors and cutaneous melanoma, but epithermal neutrons are more useful due to their superior tissue penetration compared to thermal neutrons. In this research, the tungsten carbide (WC) metamaterial is utilized as a neutron shield for neutron moderation, which is one of the numerous applications for the material that have been described thus far. Also, the source of fast neutrons is used for this purpose. The source of fast neutrons is produced by the collision of high-energy protons with the lithium target, and its energy is reduced to a certain extent by using different shields. While the source of neutrons used in BNCT is optithermal or fast, the neutrons reaching the tumor tissue interact with boron nanoparticles and the boron nanoparticles turn into compound nuclei due to neutron absorption. The created compound nucleus decays and two Li and alpha particles are produced. The stability of energy shows that the energy of Li and alpha particles can reach about 6 MeV. High-energy alpha particles interact with tumor tissue and there is a possibility of producing secondary particles in tumor tissue. In the list of secondary particles produced, there is also the possibility of producing radioactive elements that cause the tumor to become radioactive after treatment. In order to investigate the possibility of producing secondary elements produced by the interaction of alpha with tumor tissue, the Geant4 toolkit is used. In this toolkit, it is possible to check this matter by activating the spallation process. Various software such as Origin Pro is used to process the output information, the process of doing this is described below.

2. Materials and Methods

In order to check the number of elements produced in brain cancer tissue when fast neutrons are used by using the Geant4 toolkit, first the geometry, source, physics card, and how to extract data should be introduced. The simulation geometry is shown in Figure 1.

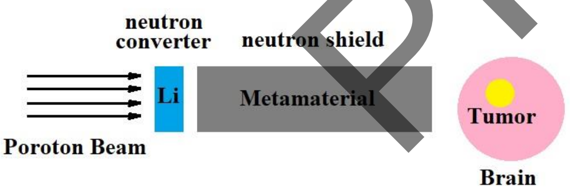

Figure 1. The geometry of simulation to investigate the production of radioactive elements in brain tumors using fast neutrons in the BNCT method

The proton source is irradiated uniformly and mainly with 35 MeV energy on a ^{7}Li target with a thickness of 1 cm to produce fast neutrons. Fast neutrons pass through the neutron shield with different types and thicknesses and some of its energy is reduced. The slowed-down neutrons penetrate the tumor tissue and interact with boron nanoparticles to produce high-energy alpha particles and ^{7}Li. By using the meshing method in the Macro program, it is possible to obtain the energy spectrum of neutrons produced from the ^{7}Li target, as well as the spectrum of slowed neutrons after the neutron shield. By defining this spectrum as a source of neutrons in the tumor, the spallation process was done using the FTFP_BERT physics in the Geant4 toolkit. By using Origin and Excel software, spallation data, which is produced in terms of mass, atomic, and neutron number of secondary elements, can be obtained. By studying the secondary particles produced in the brain tumor tissue in the BNCT method, it is also possible to investigate the radioactive elements. The simulation was done using a Dell CORE i7 laptop with a RAM of 8GB and a memory of 500 GB.

To determine the secondary particles dose in brain tumors, the number of neutrons created after the shield is first computed per proton. Next, the number of alphas produced and their energy spectrum are determined in the brain with 10B element. Finally, the energy and probability of the secondary particles at various shield thicknesses in tumor tissue are calculate by this alpha spectrum. Dose is the total energy of secondary particles per proton divided by the mass of the tumor. For converting of alpha and secondary particles dose per 1mA, the result must be multiplied by the number of the proton(N) per 1mA proton current (I=1 mA) (N=tI/e=1×1E-3/1.6E-19= 6.25E15) (the e is the charge of electron and t is irradiation time).

3. Results and Discussion

Figure 2 shows the energy spectrum of neutrons generated by 36 MeV proton irradiation of the Li target. The neutron energy was reduced exponentially up to 36 MeV. A small peak was observed at the 6 - 7 MeV energy. Also, a peak was seen larger than 36 MeV that results from the adding Li spallation energy to irradiation proton energy.

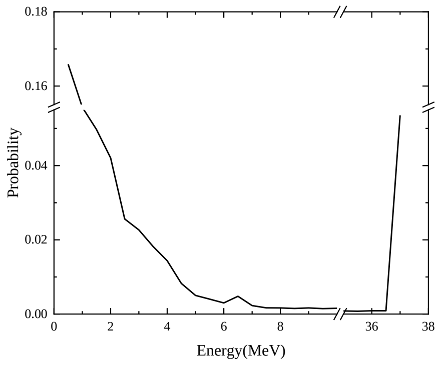

Figure 2. The neutron spectrum generated by proton irradiation on Lithium converter

By placing a tungsten, W_2B_5, and WC metamaterials as a neutron shield, the reduction of the energy of the neutron beam produced after the lithium target was calculated, and the results of W_2B_5 and WC are shown in Figure 3.

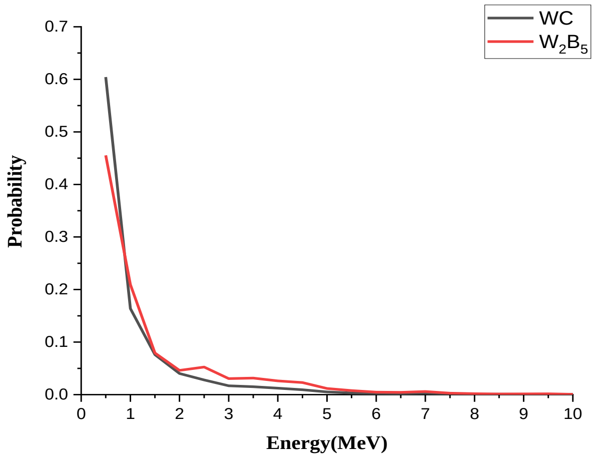

Figure 3. Comparison of WC and W_2B_5 metamaterial shields in reducing the neutron energy

The ability of WC and W_2B_5 metamaterial shields for reducing the neutron energy shows that the WC is better metamaterial than W_2B_5 for neutron moderation. The behavior of WC metamaterial for neutron moderation as a function of thickness was calculated and the result is shown in Figure 4.

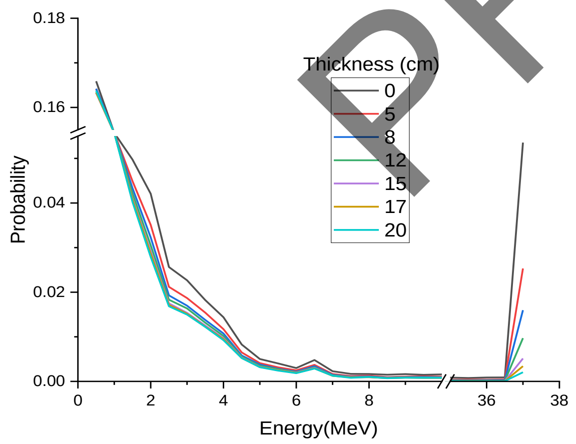

Figure 4. Neutron energy spectrum after WC metamaterial versus thickness

Table 1 compares the decrease or increase percentage of thermal and fast neutrons versus thickness according to Figure 4 data.

As shown in Table 1, the production percentage of thermal neutrons increase with the increase in thickness. The rise in thickness also results in a drop of fast neutrons, and this decrease coefficient is constant above 17 cm. The change in thickness above 17 cm will have little effect on the decrease in fast neutrons, however. Therefore, it may be expected that a thickness of 20 cm results in a reduction of almost 97% of fast neutrons and an increase of nearly 91% of slow neutrons. The percentage rise and reduction in thermal and fast neutrons is consistent beyond this thickness. More than this thickness is therefore not cost-effective.

The results of Figure 4 shows that the WC metamaterial shield with a thickness between 17 and 20 cm has the same ability to reduce neutron energy. Therefore the 20 cm shield can be regarded as the proper thickness for reducing neutron energy. Additionally, compared to other thicknesses, this thickness has a greater neutron reduction for neutron energy of more than 35 MeV. The neutron absorption by ^{10}B can lead to the production of lithium and alpha particles, the energy spectrum of which was shown in Figures 5 and 6. Lithium and alpha are more likely produced at energies below 2 MeV than other energy. Figures 5 and 6 show the possibility of production of alpha particles with an energy of 12 MeV and Li particles with an energy of 23 MeV.

According to Figure 7, the probability of proton production by the interaction of alpha particles with a tumor in different thicknesses of the WC shield is almost constant, but for shields with a thickness greater than 17 cm (i.e. 20 and 30 cm), the possibility of proton production is more than other. Electrons are produced in tumor tissue with a lower probability than protons. The same behavior can be observed for the production of photons, with a difference that the probability of producing photons for a thickness of 20 cm is more than for other thicknesses. There is the same behavior for the production of neutrons and positrons, but the probability of their production is less than electrons and other secondary particles.

Table 1. Comparison of the decrease or increase percentage of thermal and fast neutrons versus thickness

Thickness (cm)	8	10	12	15	17	20
Percentage of thermal neutrons	1.01	1.29	3.19	4.63	7.51	24.20
Percentage of fast neutrons	49.37	19.83	13.50	6.75	2.11	1.69

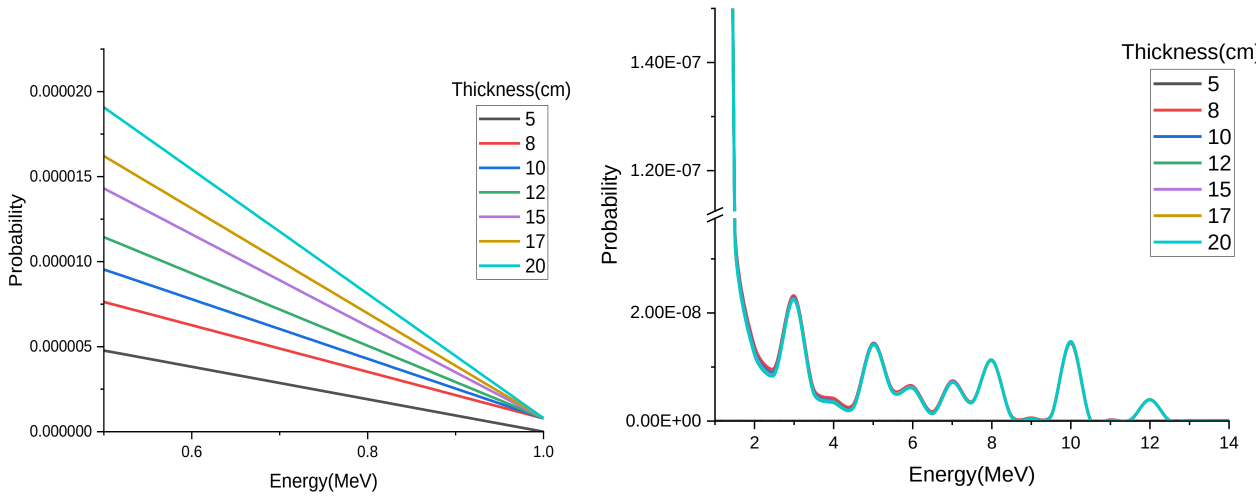

Figure 5. Energy spectrum of alpha particle production by ^{10}B decay a) less than 1 MeV, b) large than 1 MeV

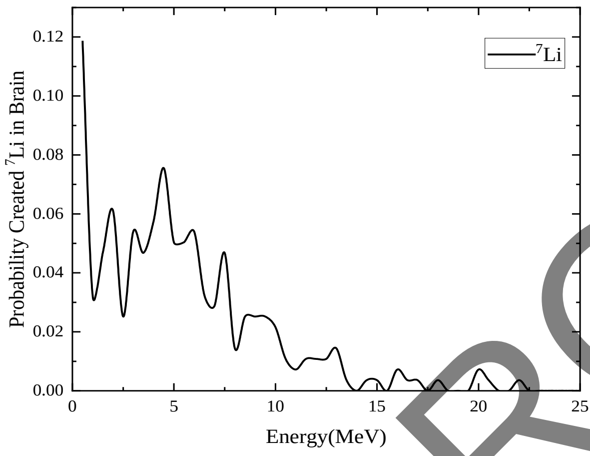

Figure 6. Energy spectrum of ^{7}Li particle production by ^{10}B decay

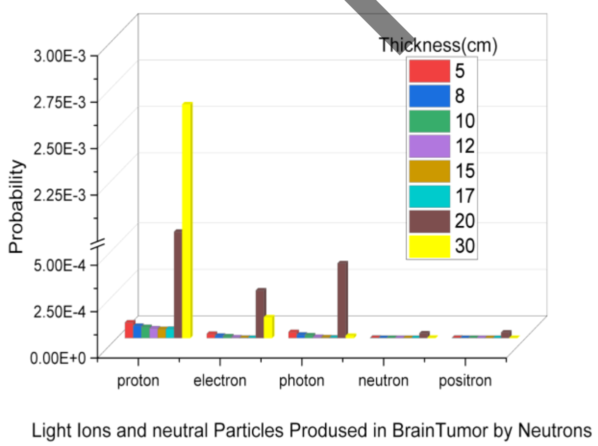

Figure 7. Probability of light ions and neutral particles production by the interaction of alpha particles with a brain tumor in different thicknesses of the WC shields

Figure 8 shows the production of ^{14}C, ^{18}F, and ^{19}Ne radioactive elements in the brain tumor by the interaction of alpha particles by the decay of ^{10}B. The production of 18F and ^{19}Ne in a 20 cm thickness of WC shield is significantly larger than ^{14}C in a 30 cm thickness. But generally, the production probability of ^{18}F is higher than that of ^{19}Ne and ^{14}C. The probability of ^{14}C production is smaller than others.

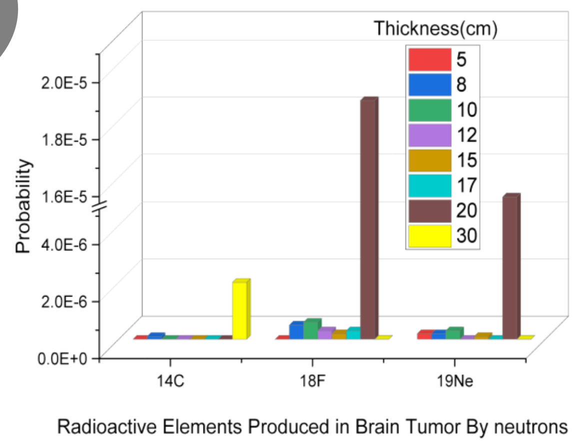

Figure 8. Production of radioactive elements in the Brain

Figure 9 demonstrates that more secondary particles are formed in thicknesses of 20, 12, and 5 cm than other thicknesses. The smallest secondary particle yield has been produced with a 30 cm WC shield thickness. The thickness of 17 cm is the most appropriate thickness for the neutron shield, as a result of secondary particle production as shown in Figure 10. The secondary particles and radioactive elements produced by this shield are lower than thicknesses.

Figure 11 also illustrates the possibility of producing different elements in different thicknesses of the WC shield from 5 to 30 cm. At first, a decreasing trend is seen up to the thickness of 17 cm, and the least secondary elements are produced in the thickness of 17 cm. The secondary particles then increase as thickness grows beyond 20 cm. Therefore, the thickness of a 17 cm is the best thickness for the WC shield.

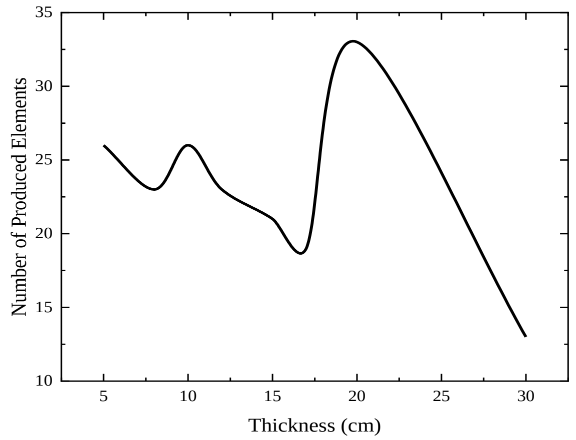

Figure 9. Secondary particles are formed in thicknesses

For dosimetry investigations, the energy of secondary particles is just as crucial as the number of secondary particles. The findings of Figure 12 demonstrate that the total energy of the secondary particle is higher in thicknesses of 8 and 17 cm than in other thicknesses. The mass and energy of secondary particles are crucial factors in dosimetry calculations in addition to the energy and number of secondary particles. Table 2 provides the result of the secondary particle dosimetry calculation

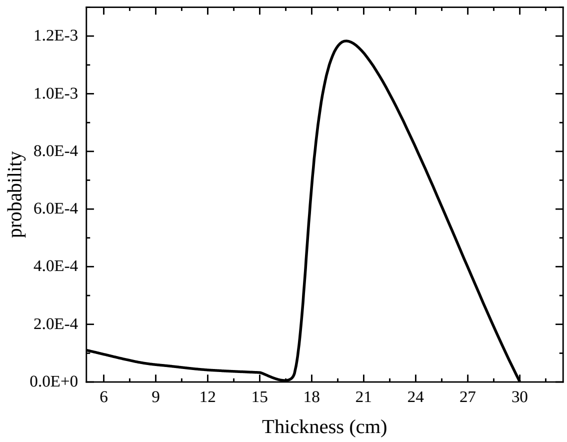

Figure 10. Probability of secondary particles production

The result of Table 3 demonstrate that the thickness of 10 cm is the most suited thickness for the neutron shield because Fe were secondary particles are produced in brain tumor than other thicknesses. In the BNCT approach, alpha generation is crucial for eliminating malignant tumors' result of alpha particles Dosimetry in the tumor tissue reveals that the quantity of alpha dose decreases by 9% for shield thicknesses ranging from 5 to 30 cm. The dose of alpha particles is reduced by approximately 6% from the thickness of the WC shield thicknesses ranging from 10 to 30 cm. Therefore, there are 94% coincidence for consideration of WC metamaterial with 10 cm thickness as a neutron shield for neutron production in proton-lithium spallation in cancer treatment by the BNCT approach.

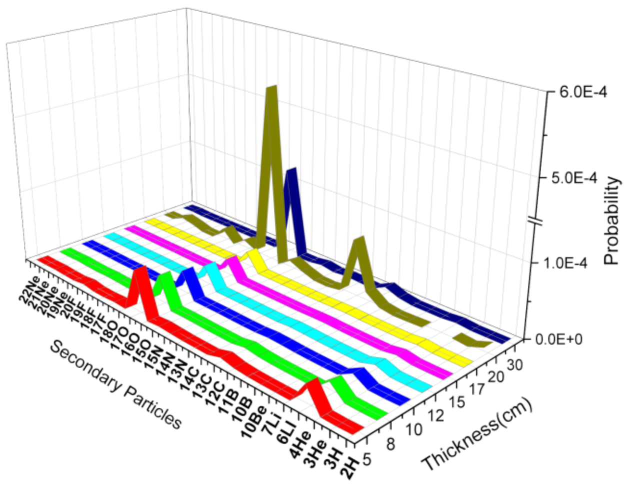

Figure 11. The possibility of producing secondary particles in different thicknesses of the WC shield in brain tumors

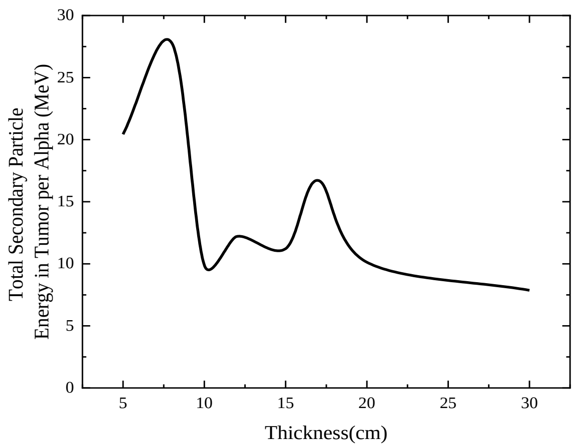

Figure 12. Total Secondary Particle Energy in Tumor per Alpha versus metamaterial shield

4. Conclusion

The aim of this research is to introduce the metamaterial as a neutron shield in the BNCT method with a fast neutron produced by the irradiation of lithium by high-energy proton in two stages. In the first stage, the neutron spectrum from proton irradiation with different energies on the lithium target was obtained which is similar to the simulated spectrum in this research, with the difference that in the simulation, due to the spallation process, neutron energies are larger than the energy of the irradiated protons. P. Y. lee *et al.* showed that the D_2O has superiority over PbF_4 and CaF_2 material from the viewpoint of fast neutron contamination control [16, 17]. Various materials such as W, Ni, lead or a combination of borated-polyethylene coupled with Pb have been used as neutron shields in BNCT [18-21]. In this research, it has been tried to investigate the possibility of using metamaterial, which has a high coefficient of thermal conductivity compared to these materials. This metamaterial has been employed as an accelerator as well as a shield against Am-Be neutrons (WC and W2B) [22, 23]. The purpose of radiation shielding is to limit radiation exposure in controlled and uncontrolled areas [19]. The optimized thicknesses of shields and their materials are determined in such a way that the equivalent dose rate delivered behind the shields would be lower than the maximum allowable dose rate recommended by the NCRP Report (2005) [19, 24]. As a result, in this study, the shield power of neutrons was compared with tungsten, the old material of the WC, and W_2B metamaterials as new shields. When it comes to neutron slowing, WC outperforms tungsten. The results show that the ability of metamaterial Graphen/WC and Graphen/W_2B_5 in neutron shielding is more than the previous shields. The suitable thickness of metamaterial Graphen/WC for neutron shield is equal to 20 cm, which is less than 30 cm for lead and graphite shield [25]. The appropriate thickness for the metamaterial materials for the neutron shield is then determined in the subsequent stage, and the findings indicate that at a thickness of 20 cm, about 98% of fast neutrons decrease and approximately 99% of slow neutrons rise. Another crucial component of the BNCT approach. The neutron absorption by ^{10}B in the tumor, which produces the alpha interaction, is what causes the secondary particle creation. After BNCT therapy, some of the secondary particles generated pose a radiation risk since they are radioactive. The likelihood of creating secondary particles in the tumor was also looked into by inserting the WC metamaterial shield, and the results indicate that the radioactive elements ^{14}C, ^{19}F, and ^{18}Na are formed in the tumor. Altering the shield's thickness allowed researchers to examine the pace at which these components are produced. One of the disadvantages of the BNCT method is the possibility of producing radioactive elements in the tumor and its adjacent tissues [26]. In this research, it has been tried to calculate the

Table 2. Secondary particles production by alpha spallation interaction in brain tumor

Thickness (cm)	Number of Neutron After Metamaterial Shield per Proton	Probability of secondary Particle production Per Proton	Total Energy of secondary Particles per Alpha particle (MeV)	Dose of Secondary particle per imA proton current (Gy/mA-proton)
5	0.000146832	2.57467E-07	0.000711434	7.46E-03
8	0.000151248	2.6521E-07	0.000108329	7.20E-04
10	0.000151524	2.65694E-07	3.46738E-09	1.73E-08
12	0.0001518	2.66178E-07	9.06683E-05	3.75E-04
15	0.0001518	2.66178E-07	8.80772E-05	2.64E-04
17	0.0001518	2.66178E-07	0.000104358	2.39E-03
20	0.000152076	2.66662E-07	0.000990026	1.11E-01
30	0.000152076	2.66662E-07	0.00101	6.50E-04

Table 3. Alpha particles caused by spallation interaction in brain tumor

Thickness (cm)	Number of Alpha in tumor per Proton	Average of Alpha Energy (MeV)	probability alpha production	alpha dose (Gy/mA-proton)
5	0.00000021	0.604560614	3.08347E-05	17.7537688
8	0.00000021	0.574811697	3.17621E-05	17.38782391
10	0.00000021	0.565454721	3.182E-05	17.13599224
12	0.00000021	0.561145306	0.000031878	17.03637148
15	0.00000021	0.557019949	0.000031878	16.91112565
17	0.00000021	0.555624247	0.000031878	16.86875213
20	0.00000021	0.554906368	3.1936E-05	16.87758817
30	0.00000021	0.534506	3.1936E-05	16.25710689

appropriate thickness for the metamaterial in such a way that, in addition to complying with the above condition, the least radioactive elements are produced in the tumor tissue.

M. Chiara *et al.* showed that the ^{38}Cl, ^{42}K, and ^{59}Fe radioactive element was produced by neutron activation of the brain, soft tissue, and other organs in the BNCT method.

But this research tried to calculate the radioactive elements produced in tumor tissue as a result of the interaction of the alpha particles produced by $^{10}B(n,a)^{7}Li$ reaction in the BNCT method, which include ^{14}C, ^{18}F, and ^{19}Ne radioactive elements. The findings demonstrate that the possibility of reducing radioactive elements is lower in WC metamaterial with a thickness of 20 cm compared to other thicknesses and that WC metamaterial with a thickness of 20 cm can be used as a shield for fast neutrons in the BNCT method with a neutron source produced by lithium bombardment with protons with a 35 MeV energy. Other beams are useless for activating the boron contained in the tumor in the BNCT procedure; only neutrons are effective. Consequently, increasing the thickness is beneficial if it boosts the thermal neutron flux while lowering the secondary particles generated in the tumor. The findings of this paper demonstrate that 20 cm is the thickness that is best suitable for this use.

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