IMPROVING NEUTRON FLUX BY OPTIMIZING THE GEOMETRIES AND MATERIALS OF THE COLLIMATION ASSEMBLY FOR FAST NEUTRON THERAPY

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Neutron therapy is extremely effective method for cancer treatment because of the relatively bigger radiobiological effectiveness (RBE) compared with accelerated electrons and gamma-rays effects on tissues. The geometry and material of the collimation system beside the neutron source are crucial elements for patient treatment with more sufficient absorbed dose rates with considering the other parameters. These reasons give valuable role for constructing and designing the assembly of collimator and source–collimator parameters in the most optimized way. Monte Carlo N-Particle Transport Code (MCNP) was used to optimizethe geometrical design and materials of the collimator at the neutron therapy center of Tomsk Polytechnic University, which uses 13.6 MeV deuteron beam bombarded with thick beryllium target to produce fast neutrons used in tumor treatment. Carried out simulations indicated the possibilities of enhancing the flux of fast neutrons and the absorbed dose rate by a factor of 3 more. Also the results showed the ability of using narrow irradiation fields with comparable results with wide-aperture collimator designs by modifying the existed one. This leads to minimize the spending time for treatment and delivering more fast neutrons and dose rate to the treated tissues.

Ключевые слова: *neutron therapy, fast neutron, absorbed dose rate, cyclotron, collimator, beryllium target*

Introduction

Neutrons are special particles and yet important tool used for various applications: nondestructive testing, treatment of the cancer, analysis of the different substances or even in fusion applications. These varieties of applications need different types of neutrons. Until now, many researches were focused on increasing the intensity of neutrons by studying and modifying the structure and component materials. According to the work of T. Schoenfeldt's, ^{208}Pb was adopted as spectrum moderator and reflector filter for the neutron source[1]. In the work of Victor de Haan's, research showed that the thin structured moderator can increase the neutron flux by factor of 10 [2]. While, E.B. Iverson showed a new way of collimation assembly to obtain more sufficient slow neutrons. The neutron flux can be enhanced by using special materials. The neutron scattering affected by moderator sizes and materials at the spallation neutron source was investigated [3]. The materials and structural components are calculated in these studies [4]. It requires huge amount of calculations and the desired results were not achieved. On the other hand, the effects of materials and structural components on the spectrum of neutrons and gamma rays can be simulated by the Monte Carlo transport code MCNP [5, 6].

Fast neutrons are highly indirect ionizing particles and have high linear energy transfer (LET) which has restricted role in radiation oncology. They are differentiated with photons and electrons in followings: (1) the fast neutrons have biologic effectiveness much less affected by a hypoxic environment; (2) the lethal effects of fast neutrons

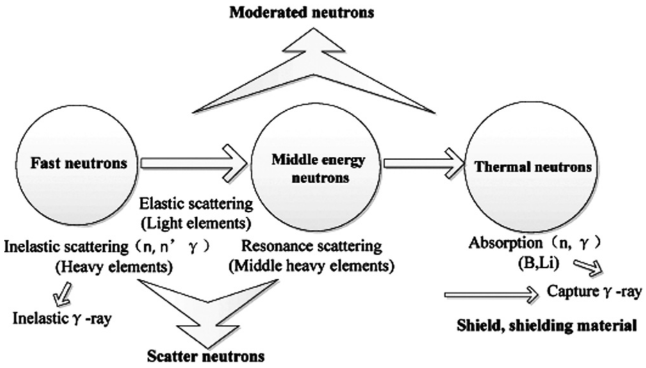

Fig. 1. *The various types of neutron interactions with materials*

are less dependent on the cell cycle phase compared with photons; (3) the recovering process of sub-lethal damage in malignant cells matters less; (4) fast neutrons are biologically more effective (RBE >2.6).

Collimator design

The collimator designs were researched to obtain more desired characteristics of neutrons, such as the absorbed dose rate, the energy of certain range (fast neutrons). The fast neutron therapy needs relatively high energy neutrons in the range between 1–20 MeV depending on the region and depth of the treated tissues, it requires as low as possible slow and scattered neutrons. For this reason, the structure and materials of the aperture, collimator components are needed to be designed carefully. According to the procedures of fast neutron therapy, it needs the neutrons in fast neutron range as high as possible and other parts of spectrum of neutrons and gamma or X-rays as low as possible.

The neutron beam with various properties can be generated by neutron interactions with different structures and components of the materials as shown in Fig. 1. The heavy metal elements, such as tungsten and iron, slow down the fast neutron well by the inelastic scattering. Then the low-Z elements reduce the moderated neutrons to thermal neutrons by elastic scattering and resonance scattering. At the end, some elements, such as the boron and lithium, capture the thermal neutrons and emitting secondary gamma-rays. Because of these interactions, neutron spectrum will change accompanying with changes in the energy deposition, absorbed dose rate and the neutron beam profile. The neutron energy is continuously reduced by the interaction of neutron with the material' nuclei. Here, the neutron scattering contains elastic and inelastic scattering. The inelastic scattering dominates in fast neutron range and the elastic scattering dominates in medium energy range. The energy of neutrons is reduced by inelastic scattering when the energy of neutron is high. After the energy of neutron reaching to a threshold value, the neutron is slowed down by the elastic scattering [7].

The set-up of simulations

The collimator consists of many individual and separated parts; non-removable parts; the iron and concrete parts which is about 42 cm in length and removable polyethylene part 45 cm, as shown in Fig. 2.

The simulations were carried out with fast neutrons generated by deuteron beam current 30 microampere with energy of 13.6 MeV bombarded with 2 mm thick beryllium target and 5 cm in diameter. The neutron spectrum were extracted from the results of LISE++ simulations of the outputs of reaction ^{9}Be(d, n) at 13.6 MeV and at the 0° zero degree emittance (forward direction). These results are comparable with other experimental results with small differences as shown in Fig. 3. And then were deposited in the input files of MCNP-4C code.

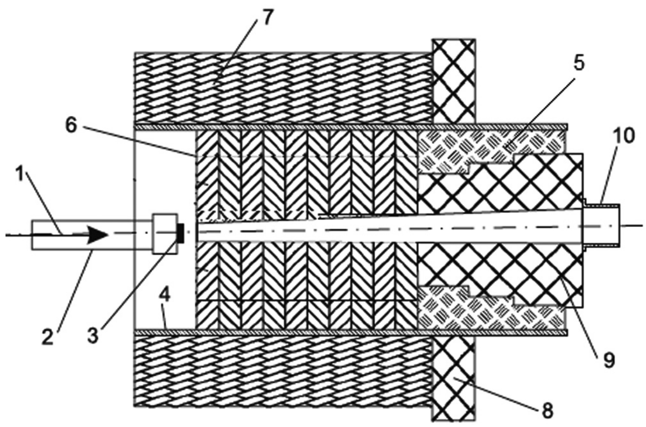

Fig. 2. *Neutron beam collimator. 1 – deuteron beam; 2 – ion beam channel; 3 – Be target; 4 – iron pipe; 5 – polyethylene collimator; 6 – iron disks; 7 – concrete wall; 8 – radiation protection of polyethylene; 9 – removable polyethylene collimator; 10 – cone*

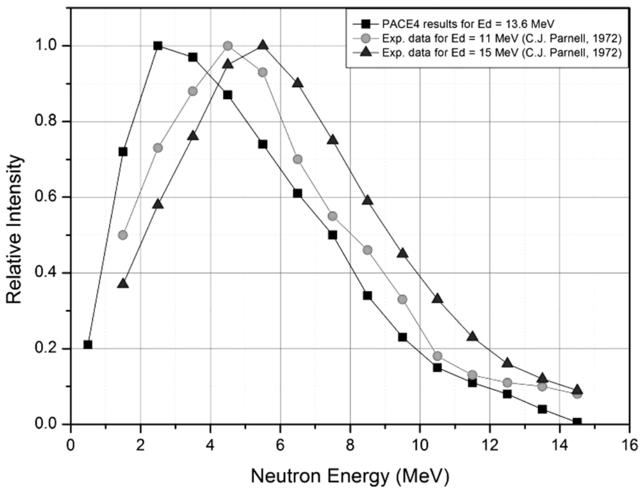

Fig. 3. *The results of PACE4 code and experimental data were taken from work of C. J. Parnell, 1972*

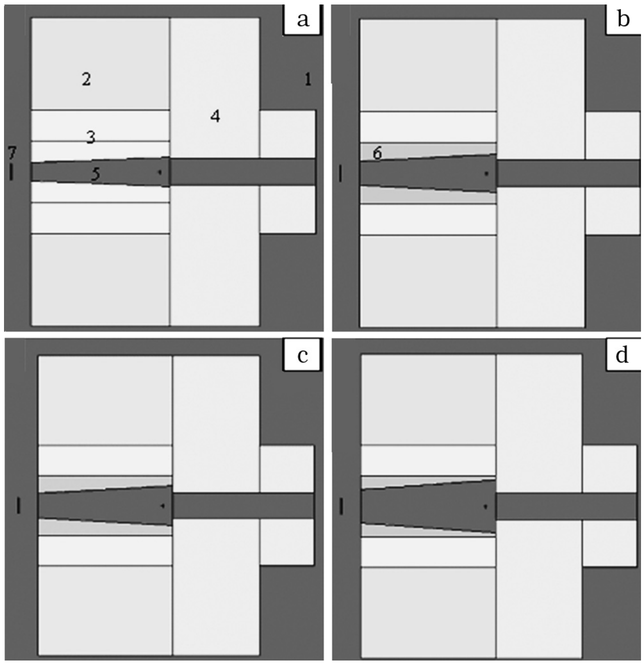

Fig. 4. *The MCNP5 geometries and materials of collimator parts; 1 – air, 2 – concrete, 3 – iron, 4 – polyethylene, 5 – air cone, 6 – lead metal, 7 – beryllium target*

Results and discussions

Case 1: Studying the effect of changing the sizes of the collimator aperture with lead inner layer

Eight different aperture-related values have been simulated and indicated in the MCNP-4C input file as the parameter ($tg^2\theta$) of the inner conical of the first half of the collimator as shown in Tabl. 1. While the second half is a cylinder of polyethylene with squared-shaped end irradiation field 8.5×8.5 cm^2. The detection point is concentric with the collimator axis at a distance 105 cm from the beryllium target. Considering that the target beryllium with diameter of 5 cm at 6 cm from the entrance of collimator cone (see Fig. 4).

The results are presented in Tabl. 1. It contains the values of aperture radius for every selected θ and the end radius of the cone. Also, the thickness of metal lead which examined because of its desired inelastic scattering properties for fast neutrons.

Table 1

the aperture sizes as MCNP parameter ($tg^2\theta$) and their corresponding neutron flux and absorbed dose rates

MCNP parameter, $tg^2\theta$	Radius of begin and end of the cone, cm		Thickness of lead (Pb) at the begin and end of the cone, cm		Neutron flux density at 105 cm from source, $(n/cm^2/s)\times10^8$	Neutron dose rate at 105 cm from source. Gy/min
	begin	end	begin	end		
0.0018	3	4.8	0	0	1	0.15
0.003	3.9	6.2	6.1	3.8	1.47	0.225
0.0035	4.3	6.7	5.7	3.3	1.67	0.237
0.0038	4.5	7	5.5	3	1.66	0.239
0.004	4.5	7	5.5	3	1.67	0.238
0.004	4.5	7.2	0	0	1.45	0.215
0.005	5	8	5	2	1.44	0.2
0.006	5.5	8.7	4.5	1.3	0.997	0.125

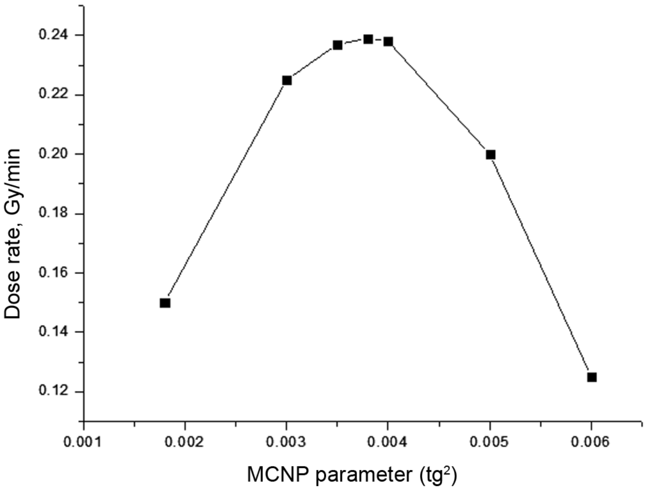

Fig. 5. *Illustration of relationship between the aperture sizes of collimator and the variation of neutron flux and corresponding absorbed dose rate*

The yellow row indicated the old existed design of collimator without any improvements where the neutron flux is about 1×10^8 n.cm^{-2}.s^{-1} which is equivalent to absorbed dose rate 0.15 Gy/min. These results are with good agreement with other experimental and theoretical works .[8] The green row refers to about 60 % dose rate improvement just by increasing the aperture without any additional layers of Lead metal. Although, by replacing lead layer instead of iron layer in the inner part can also enhance the neutron flux and consequently the dose rate farther to 70 %. These results are presented in the Fig. 5.

From Fig. 5, it is noticeable that there is a limit diameter of aperture where above this value the dose rate will begin decreasing instead of increasing. This can be referred to the loss of fast neutrons after scattering from the inner layers and cannot contribute to the main neutron beam which in this case far from the inner layer when the aperture size is big enough.

Case 2: Studying the effect of adding lead metal piece in front of the neutron beam direction

The effects of adding a lead metal beside and in front of the beryllium target have been simulated with various possibilities of lead thicknesses and for different aperture diameters. In the beginning, other metals like; In, Ir and Yb have been studied by MCNP-4C code and their effects on the neutron spectrum and flux. But, the best results were for lead metal because of the large cross-section of generating new secondary neutrons 2.5 b for (n, 2n') interactions in the fats neutron spectrum. Also, due to the ease dealing with this metal and the cheap price comparing with the others. The best results of gaining more neutrons in the fast range were for the lead metal with thickness 3.5 cm. In this case, a 70 % gained neutrons were obtained just by placing 3.5 cm of Pb metal in front of the beryllium target in the direction of the neutron beam (fig. 6).

It is very important to mention that these good results occurred when the aperture size is relatively small, about 5 cm in diameter. But when the aperture size is larger, in this case, when a piece of Pb metal was placed, the neutron flux was

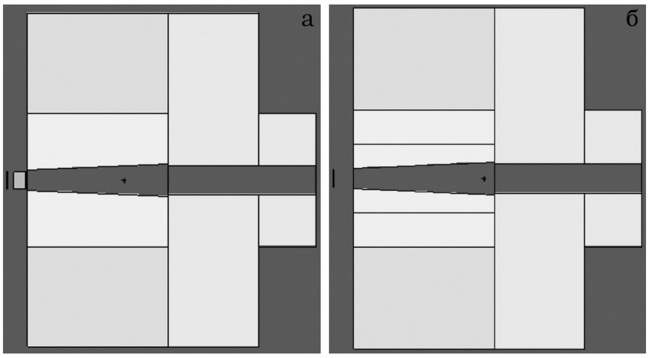

Fig. 6. *The MCNP5 illustration of the collimator in the treatment room with the Be-target and (on the right) the same collimator with the Be-target + 3.5 cm Pb (on the left)*

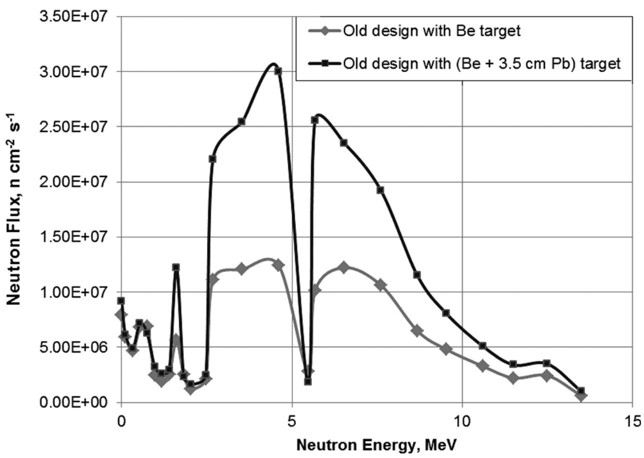

Fig. 7. *The neutron spectrum of the two cases; first, the beryllium target. Second, the beryllium target + 3.5 cm Pb*

decreased. So it is better for a collimator with a big aperture size not to use any metal beside the beryllium target.

From Fig. 7, an obvious increase about 70% of desired fast neutron flux have been gained in the neutron spectrum due to the (n, 2n') interactions in the 3.5 cm thick Pb metal.

Case 3: Studying the effect of aperture diameter with additional lead layer

In this case, many different simulations and variants of materials and thicknesses were carried out to reach the most gained and sufficient arrange of geometry and materials. And the final design results (see Fig. 8) were 300 % more than the old design of neutron flux and dose rate mostly in the fast spectrum region.

The old design had an aperture with diameter of 5 cm and the new one had 13 cm. the old design had no additional materials despite the iron metal. While, the new one had gradually decreasing in thickness lead metal layer with initial thickness 3.5 cm and final thickness 0 cm at the beginning of the polyethylene part of the collimator (as shown in Fig. 8). In addition, the old design had a fixed diameter of cylindrical polyethylene with irradiation field 8.5×8.5 cm^2. Instead of this, the new design had a conical polyethylene shape with initial diameter of 20 cm and 8.5 cm at the end.

As illustrated in Fig. 9, the neutron flux density of the old design for 13.6 MeV deuteron ions with current 30 μA is equal to 1×10^8 n cm^{-2} s^{-1} and the dose rate is 0.15 Gy/min. while the neutron flux for the new design reached the value 3×10^8 n cm^{-2} s^{-1} and the dose rate of 0.45 Gy/min. The good results of the new design due to a small layer of lead metal located on the inner layer of metallic iron. In addition, it refers to the large opining angle of the collimator which permits more collections of neutrons and reflect the original and scattered neutrons to the main neutron beam stream. The neutron spectrum of the new design showed an increasing of the thermal neutrons by factor of 5 more than the old one. But, it can be reduced by inserting a 3 cm Pb metal piece in front of the beryllium target as a filter.

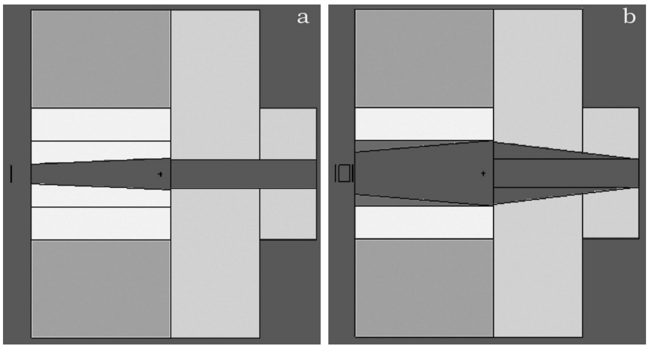

Fig. 8. *The MCNP5 geometries and materials of the old and new design of collimator*

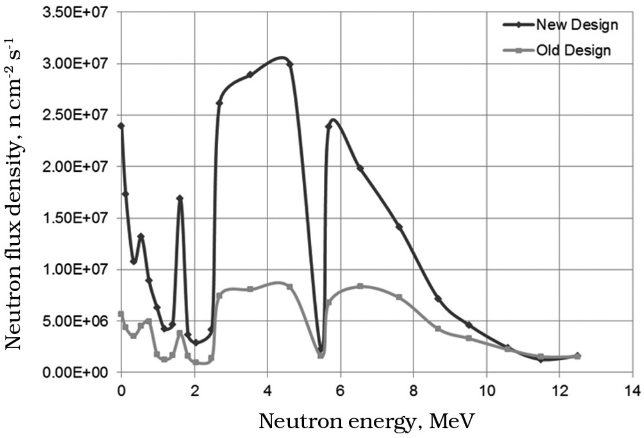

Fig. 9. *Illustration of the neutron spectrum of the two collimators; the old design and the new design*

Case 4: Studying the effect of changing the geometry of polyethylene part with additional metal layer

In this case, the first half of the collimator neither changed geometrically nor additional layers or new materials have been added. The changes carried out for the second cylindrical polyethylene part of the collimator. The purpose of this case to measure and examine the neutron flux and spectrum for small irradiation field at the end of polyethylene part 2 cm and less in diameter as followings (see Fig. 10):

From Fig. 10, A – removable polyethylene collimator with a central cylindrical channel with a diameter of 2 cm. B – removable polyethylene collimator with a conical channel with an end diameter of 2 cm. C – removable polyethylene collimator with a conical channel with a diameter of the end 2 cm covered by a thickness of 1 cm of Pb layer in the inner surface. D – removable polyethylene collimator with a conical channel with a diameter of the end 2 cm covered by a thickness of 2 cm Fe layer in the inner surface.

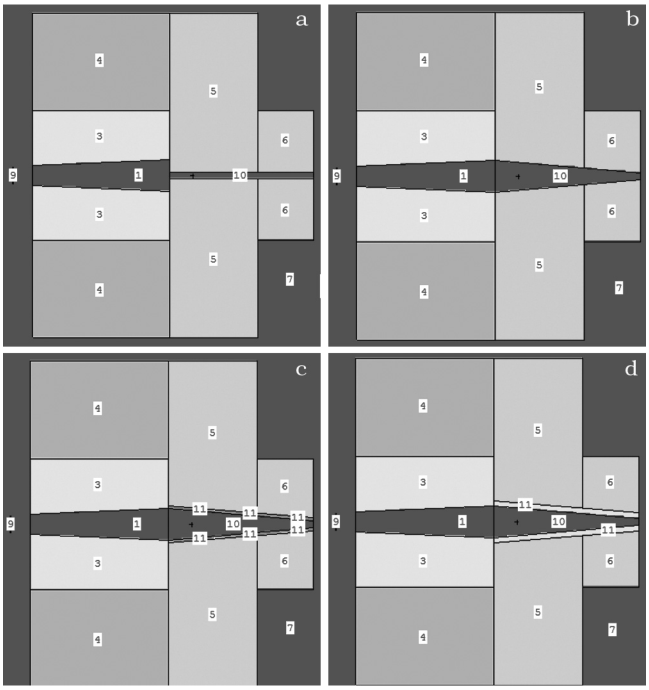

Fig. 10. The MCNP5 illustration of different geometries of the polyethylene part and additional layers of Pb and Fe with different thickness

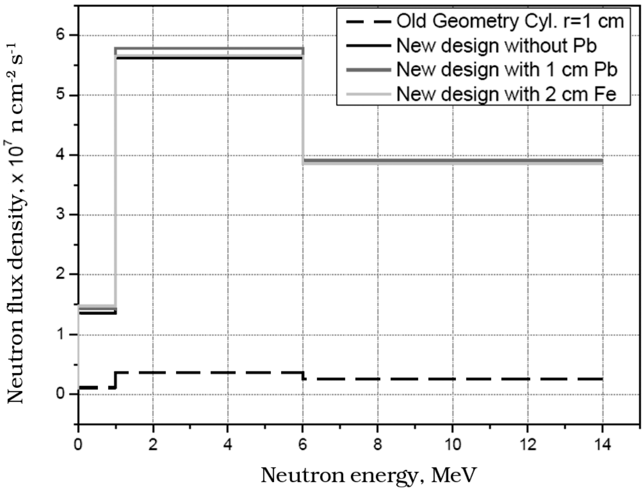

Fig. 11. MCNP simulations results of the cumulative neutron intensity over three energy bands; 0 – 1 MeV, 1 –6 MeV and 6 – 14 MeV for A, B, C and D geometrical design of the collimator

The results of the dose rates and neutron flux density of the four scenarios are presented in Tabl. 2. Which are compared with results of fixed-diameter cylindrical polyethylene collimator with irradiation field of 4.5×4.5 cm^2.

The Tabl. 3 describes the neutron flux density for each components and energy ranges of spectrum from thermal neutrons to fast neutrons. The scenarios B, C and D are almost identical and the differences between them are negligible. A significant enhancement in neutron flux density by a factor of about 15 times more between the designs B, C, D and the initial design A. Which indicates for small irradiation field applications that the col-

Table 2

The MCNP-4B Simulation results of the four scenarios and other example for comparison (the last column)

	A	B	C	D	4.5×4.5 cm^2 collimator for comparison
Doses, Gy / min	0.012	0.174	0.177	0.175	0.17
Total Neutron Flux, $\times 10^8$ n $cm^{-2}.s^{-1}$	0.078	1.10	1.12	1.11	1.07

Table 3

The MCNP-4B Simulation results of the four scenarios and other example for comparison

	Neutron Flux, $\times 10^7$ n $cm^{-2}.s^{-1}$			
	E < 0.4 eV	0.4 eV < E <1 MeV	1 MeV < E <6 MeV	6 MeV < E <14 MeV
A	0.055	0.11	0.36	0.26
B	0.12	1.36	5.63	3.92
C	0.13	1.43	5.79	3.91
D	0.085	1.47	5.66	3.86

limator design can be modified in a certain way to reach as same as the neutron flux and dose rate for big irradiation fields.

Fig. 11 is showing the results in Tabl. 3 which obviously demonstrated the significant improvement on the neutron flux in the collimator when the polyethylene part for narrow irradiation fields is modified.

Conclusions

In all studied cases, remarkable gains of fast neutrons have been obtained. Especially, the 300 % increment for relatively big aperture diameter with gradually decreasing thickness layer of Lead metal. Also by changing the cylindrical polyethylene part of assembly into a conical shape which have wider aperture diameter. That allows more scattered fast neutrons to be collected and returned into the main stream of the neutron beam. In addition, a narrow treatment beam can be achieved by modifying the geometry and the opining angle of the polyethylene part to be a conical collimator with small irradiation field at the end 1–2 cm in diameter. This is equivalent to cylindrical collimator with big aperture diameter in giving the same fast neutron fluxes and absorbed dose rates at the treatment point or detector. So, a more efficient and precise treatment procedures can be done. Fortunately, this also can reduce the spending time for treatment with hard uncomfortable situation with the patients, beside the ability of delivering more dose rates to small areas in the patient's body. On the other hand, the same technic can be used in improving the geometry and aperture sizes and inner layer materials of the irradiation channels in research and experimental nuclear reactors. But this case is for thermal and epithermal neutrons used in BNCT radiotherapy.

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УЛУЧШЕНИЕ НЕЙТРОННОГО ПОТОКА ПУТЕМ ОПТИМИЗАЦИИ ГЕОМЕТРИИ И МАТЕРИАЛОВ КОЛЛИМАЦИОННОЙ СБОРКИ ДЛЯ ТЕРАПИИ БЫСТРЫМИ НЕЙТРОННАМИ

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Поиск эффективных методов подавления роста злокачественных новообразований является актуальной задачей радиологии. Быстрые нейтроны обладают большей радиобиологической эффективностью воздействия на ткань новообразований по сравнению с быстрыми электронами или гамма-квантами и применяются для терапии радиорезистентных опухолей. Исследовано влияние геометрии и материалов коллиматора источника нейтронов на основе бериллиевой мишени и пучка дейтронов с энергией 13,6 МэВ нейтронного терапевтического канала Томского политехнического университета на характеристики нейтронного потока. Для расчётов использовали метод Монте-Карло (MCNP). Показано, что с помощью оптимизации геометрии и материалов источника быстрых нейтронов можно увеличить плотность потока и мощность дозы нейтронов, подводимой к опухоли, в 3 раза. Показано, что нейтронный пучок можно ограничить апертурой поля облучения около 1 см^2. При этом плотность потока нейтронов сопоставима с потоком нейтронов при широкой апертуре коллиматора. Результаты расчётов показывают направления минимизации затрат времени на лечение с помощью быстрых нейтронов.

Key words: *нейтронная терапия, быстрые нейтроны, мощность поглощенной дозы, циклотрон, коллиматор, бериллиевая мишень, Монте-Карло моделироавние*

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