Increasing The Flux of Fast Neutron beams used for Radiotherapy Purposes

Abdullah Shehada
Engineering School of Nuclear Technologies
National Research Tomsk Polytechnic University
Tomsk, Russia
shihada@tpu.ru

Vladimir Golovkov
Engineering School of Nuclear Technologies
National Research Tomsk Polytechnic University
Tomsk, Russia
golovkov@tpu.ru

Abstract— 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 optimize the 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.

Keywords— MCNP code, 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. Schönfeldt's, 208Pb 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.[3] The neutron scattering affected by moderator sizes and materials at the spallation neutron source was investigated.[4] the materials and structural components are calculated in these studies. 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 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 (relative biologic effectiveness RBE > 2.6).

I. 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. 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]

II. Experiment Set-Up

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.1.

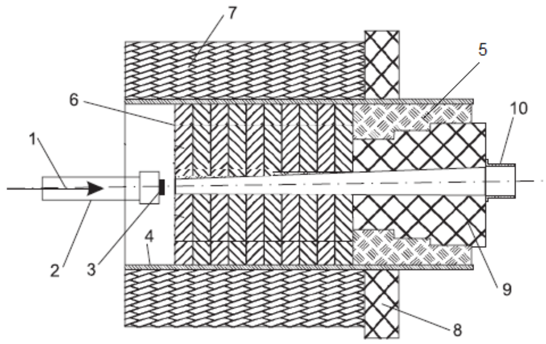

FIG 1. Neutron beam collimator. 1 – deuteron beam; 2 – ion beam channel; 3 – Be target; 4 – iron pipe; 5 – polyethylene collimator; 6 – iron disks; 7 – concrete wall; 8 – radiation protection of polyethylene; 9 – removable polyethylene collimator; 10 – cone.

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.2. And then were deposited in the input files of MCNP-4C code. equation.

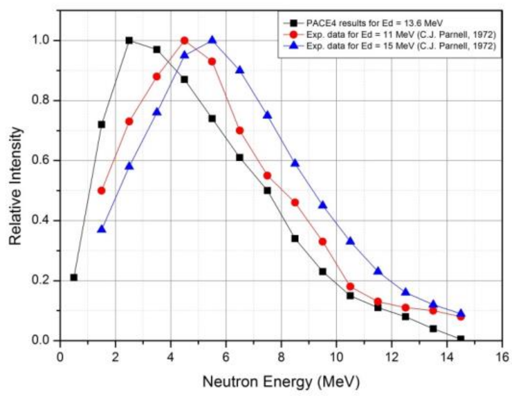

FIG 2. the results of PACE4 code and experimental data were taken from work of C. J. Parnell. 1972.

III. Results and Discussion

Eight different aperture-related values have been simulated and indicated in the MCNP-4C input file as the parameter (tg2θ) of the inner conical of the first half of the collimator. While the second half is a cylinder of polyethylene with squared-shaped end irradiation field 8.5 x 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.3).

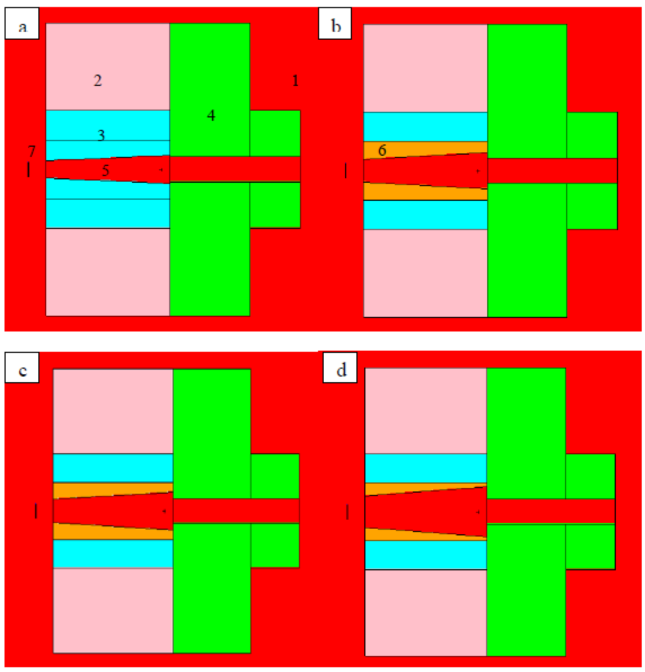

FIG 3. the MCNP5 geometries and materials of collimator parts; 1- Air, 2- Concrete, 3- Iron, 4- Polyethylene, 5- Air cone, 6 – Lead metal, 7- Beryllium target.

The results are presented in Figure 4. It contains the values of aperture radius for every selected θ. The neutron flux of the old existed design of collimator without any improvements is about 1 x 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 %.

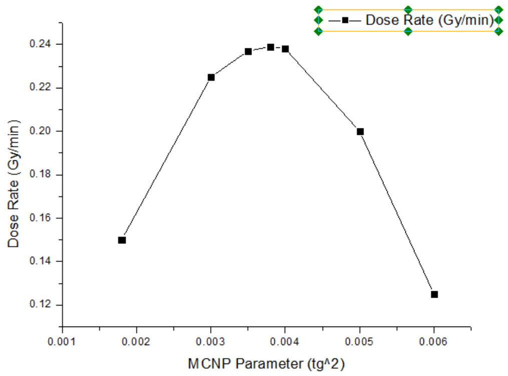

FIG 4. illustration of relationship between the aperture sizes of collimator and the variation of neutron flux and corresponding absorbed dose rate.

From Fig 4, 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.

IV. CONCLUSIONS

In all studied cases, remarkable gains of fast neutrons have been obtained. Especially, the 70% 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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