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Modified Collimator for Neutron Therapy Applications: Enhancing Narrow Beam Detection of Fast Neutrons

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In clinical practice, when working with a target that emits neutrons in 4π space, it is always required to concentrate them into a mono directional beam. This is necessary both to increase the particle flux density and to give it the desired shape and optimal cross-sectional area. In principle, the beam shape can be changed using a collimator, which makes it possible to significantly narrow it and achieve minimal neutron absorption in structural elements. In this paper, simulation works using MCNP5 code have been carried out to find the possibility and reality of applying narrow beam of 2 cm and less of fast neutrons in radiotherapy. Simulations were performed on the original design of the treatment 8.5×8.5 cm^2 collimator existed in the cyclotron laboratory of Tomsk Polytechnic University. The results showed that the neutron energy spectrum almost would not change in the fast region, but in opposite, there was about 11 % higher neutron flux when using the collimator with 2 cm aperture. The spatial distributions of fast neutrons were significantly narrower at 10 cm distance from the aperture compared to the original design 8.5×8.5 cm^2. The narrower and intense neutron beam would save the healthy tissues beside the tumor and also decrease the treatment time period which make the treatment procedures more comfortable. There is reason to hope that narrow beams will make neutron beam radiotherapy for the treatment of small and irregularly shaped tumors more accurate and safer for the patient.

1. INTRODUCTION

Neutrons are widely used in many fields. Therefore, there is a need for adapted sources of these particles. Until now, research has mainly focused on increasing the intensity of their output by improving the design and selection of component materials of the collimator.

T. Schönfeldt [1] adopted lead ^{208}Pb as a reflective filter for a neutron source. V. De Haan [2] showed that a moderator in a collimator with a fine graphite structure can increase the neutron flux by almost 10 times. E.B. Iverson [3] proposed a new design of the collimator assembly for obtaining more intense fluxes of slow neutrons.

The neutron flux can be increased by using special materials. Neutron scattering was studied, which depends on the geometry and composition of the moderator in the source of fission neutrons [4]. These studies require a large amount of calculations and the desired results have not yet been achieved. At the same time, the influence of the material composition and design on the spectrum of neutrons and gamma rays can be modeled using the Monte Carlo transport code of the MCNP type [5, 6].

Various designs of collimators have been studied to increase the flux density and improve the spectral properties of fast neutrons. Neutron therapy requires particles with energies in the range from 1 to 20 MeV, depending on the size of the area and the depth of the treated tissues. To do this, it is necessary to reduce the proportion of scattered and slow neutrons, and increase the proportion of fast ones [7, 8].

There are a number of publications in the scientific literature devoted to the influence of the geometry and materials of a collimator on the characteristics of fast neutrons produced in nuclear reactors or when light targets are bombarded with accelerated ions [9–11]. It is advisable to use it to limit the size of the irradiated medium. If the neutron source is too large, an undesirable penumbra appears on the irradiated object. The collimator will increase the flux density at a certain distance from the source, where it scatters neutrons and creates a collimated beam. The magnitude of the flux increment depends on the collimation field and the length of the collimator. On the other hand, if the neutron source is large across, the collimator may reduce the neutron flux rather than increase it. Most collimators can increase the flux density by 10–20% [9].

The main advantage of neutron therapy is that unlike gamma and electron therapy neutrons destroy damaged tissue irreversibly, i.e. there is no recurrence after neutron therapy. The negative aspects of neutron therapy are associated with affecting healthy tissues of the body.

The existing technology operates a wide horizontal beam, the direction of which we cannot control in fact. But by optimizing geometry and materials for collimator we will be able to focus the scattered neutrons to a narrow beam. A narrow beam allows introducing a safer method of irradiating tumors from different sides. Here the objective is to maximize the use of neutrons going out of the source and to focus them in such a way as to ensure a maximum therapeutic effect.

2. MEASUREMENTS AND METHOD

MCNP is a universal Monte Carlo code that can be used to transport neutrons, photons, electrons, or bound particles. Specific applications include many areas, such as radiation protection, dosimetry, radiography, medical physics, nuclear safety, detector design, design of accelerator targets, fission and fusion reactors, etc. The code handles an arbitrary 3D configuration of materials in geometric cells.

Important standard features that make MCNP easier to use include powerful source, criticality source, and surface source; both geometric and output plots; a rich collection of methods for reducing deviations; flexible calculation structure; and an extensive set of cross-section data as ENDF/B-VI for neutrons.

The collimator consists of several parts; non-removable parts; the iron (steel) collimator which is about 42 cm in length and removable polyethylene (PE) part 45 cm, as shown in Fig. 1.

Several scientific papers have been previously published dealing with optimization of the fast neutron collimator used in radiotherapy at Tomsk Polytechnic University. However, in one of these studies, a collimator ending in a nozzle with a diameter of 2 cm was used and compared with collimator' apertures of larger diameters. Nevertheless, it has not been studied if the neutron flux diverges after exiting the aperture when the end of the aperture is small (2 cm or less) compared to the case when the aperture is large (8.5×8.5 cm^2, for example). This issue is very important in radiation therapy, where the spatial distribution of the neutron beam should not be diverged, so if the beam is wide, it would expos healthy tissues to high doses. Also, the neutron flux becomes less intense in the target area (the tumor) for treatment, which increases the irradiation time required to reach the appropriate dose. In this work, the spectrum of fast neutrons and the spatial distribution of the end of a small aperture of 2 cm were studied, using simulations with the code MCNP5. The neutron spectrum used in the simulation has been accurately described in a previous work, and it is the spectrum resulting from the collision of a beam of deuteron ions with an initial energy of 13.6 MeV on a 2 mm thick beryllium target. The spectrum and transverse spatial distribution of a neutron beam were simulated at a distance 10 cm from the end of the aperture. An additional small cylindrical collimator with a diameter of 2 cm was simulated for comparison and the shape and spectrum of the beam leaving the channel were studied.

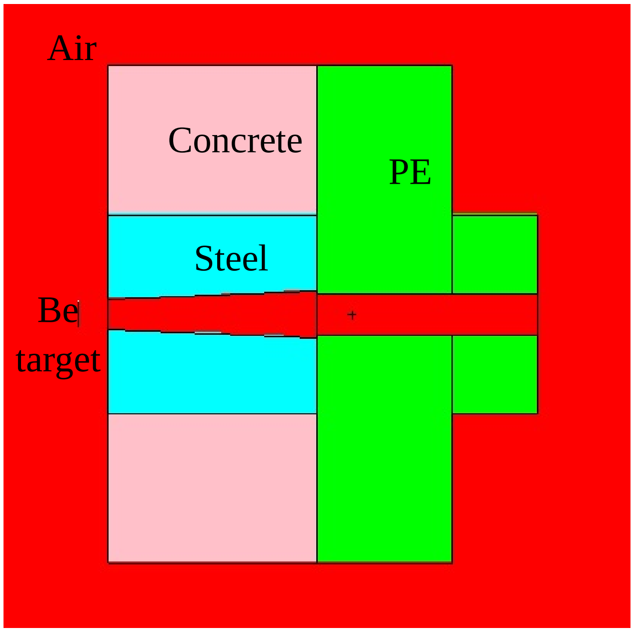

Fig.1. MCNP5 scheme of the original collimator 8.5×8.5 cm^2 deployed at the radiotherapy treatment room.

3. RESULTS AND DISCUSSION

The simulated work was carried out on the neutron collimator utilized in the radiotherapy room without any modifications (Fig.1). The results of the neutron spectrum as well as the spatial distribution were compared at a distance of 10 cm from the aperture. The simulation results were extracted for collimators with apertures diameter of 2 cm in different conditions, as shown in Figure 2. In Figure 2, an additional small collimator of polyethylene with an extension of 10 cm and a thickness of 20 cm with a cylindrical channel 2 cm in diameter was added, to investigate its effect on the spectrum of neutrons and their spatial distribution. In addition, in another step, an inner layer of lead metal (2-cm thickness) was added to the cylindrical channel of the additional part, to examine the change in the neutron spectrum and its spatial distribution, as well as the possibility of obtaining additional fast neutrons through the reaction (n, 2n).

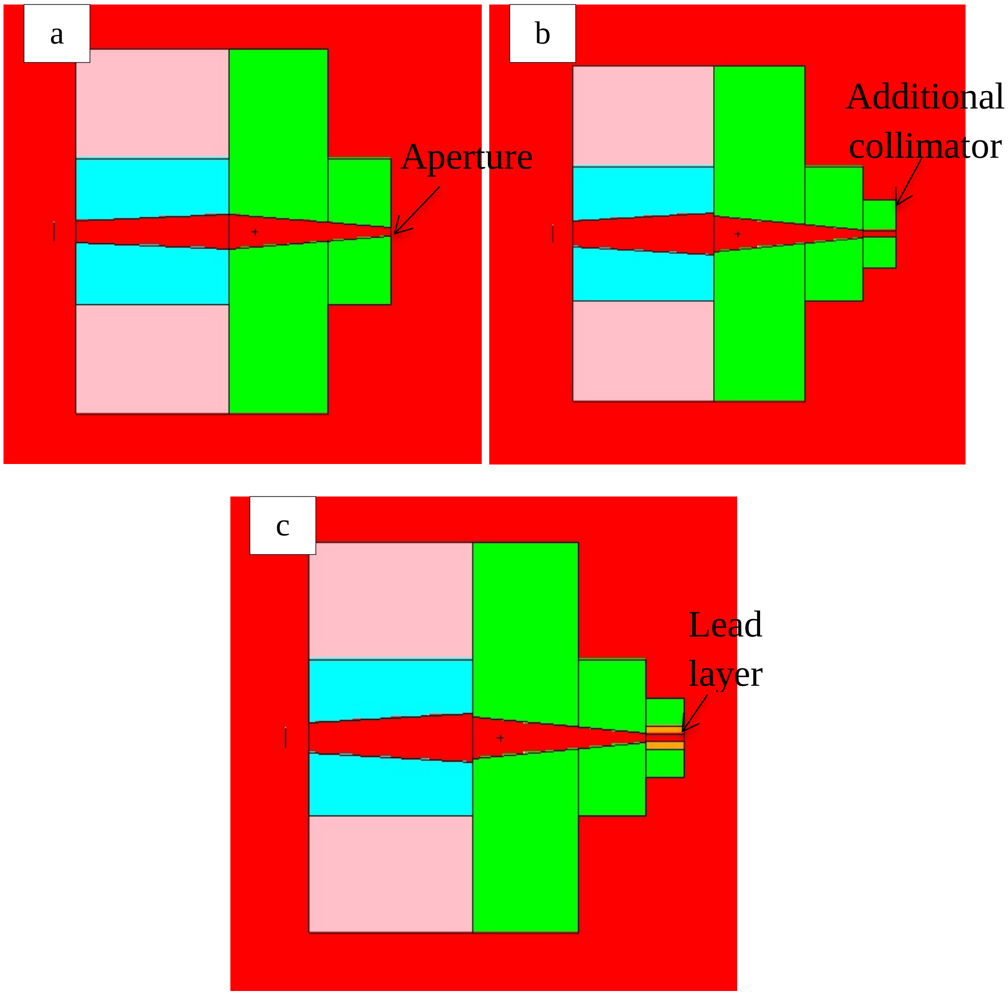

Fig.2. MCNP5 schemes of the simulated collimators; a) the collimator with 2 cm diameter of aperture, b) the collimator with 2 cm aperture and additional collimator 10 cm in length and 20 cm thickness, c) the case (b) plus an addition inner layer of lead metal.

It was found that the results of the MCNP simulation for the spectra of neutrons leaving the four different apertures of the four collimators. In general, the neutron spectra do not change in the energy range between 1 and 13 MeV. Moreover, the collimator with an aperture of 2 cm without any additional parts can increase the neutron flux by about 11 percent compared to the original collimator with an aperture of 8.5×8.5 cm^2. In addition, it can be noticed that the lower-energy (thermal) component is diluted by 3-folds when using the 2-cm aperture collimator. This result is crucial in reducing the flux of thermal neutrons in the case of radiation therapy, as it reduces the thermal neutron exposure of healthy tissues surrounding the tumor and decreasing the unnecessary radiation doses. Moreover, it is found that adding an additional small collimator of polyethylene reduces the fast neutron by about a half, but at the same time it decreases the thermal neutron flux several times. In fact, the reduction of the fast neutron flux is not considered a good feature in the field of fast neutron therapy, as it prolongs the period of radiation therapy. Furthermore, the thermal neutron flux can be reduced by a thin layer (filter) of cadmium or borated compounds. Adding lead layer did not improve the neutron spectrum and did not contribute to increasing the neutron flux. That is because of the fast neutrons have been collected by the conical collimator with an end of 2 cm, and therefore there are no sufficient amounts of fast neutrons that can collide with the inner layer of lead and contribute to the increase of the neutron flux through the reaction (n, 2n).

4. CONCLUSION

The results show that the neutron energy spectrum remains nearly unchanged in the fast region, while the neutron flux increases by approximately 11% when using the collimator with a 2 cm aperture. The spatial distribution of fast neutrons is significantly narrower at a distance of 10 cm from the aperture compared to the original design of 8.5×8.5 cm^2. The narrower and more intense neutron beam reduces damage to healthy tissue and decreases the treatment time, making the procedure more comfortable for the patient. Narrow beams offer the potential to make neutron beam radiotherapy safer and more accurate for the treatment of small and irregularly shaped tumors.

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