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VERIFICATION OF A BEAM OF EPITHERMAL NEUTRONS FOR BORON-NEUTRON CAPTURE THERAPY*

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Abstract

A promising method of treatment of many malignant tumors is the boron neutron capture therapy (BNCT). It provides a selective destruction of tumor cells by prior accumulation of a stable boron-10 isotope inside them and subsequent irradiation with epithermal neutrons. As a result of absorption of a neutron by boron, a nuclear reaction occurs with the release of energy in a cell containing boron. To measure the "boron" dose, a small-size neutron detector based on a boron-enriched cast polystyrene scintillator was proposed and developed at the BINP. The paper presents the results of changing the boron dose and the dose of gamma radiation in a water phantom and the comparison of these results with the calculated ones. The obtained result is important for irradiation of small laboratory animals with grafted tumors, large domestic animals with spontaneous tumors, and the planned clinical trials of the technique.

INTRODUCTION

A promising method of treatment of many malignant tumors is the boron neutron capture therapy (BNCT) [1]. It provides a selective destruction of tumor cells by prior accumulation of a stable boron-10 isotope inside them and subsequent irradiation with epithermal neutrons. As a result of absorption of a neutron by boron, a nuclear reaction occurs with the release of energy in a cell containing boron. To measure the "boron" dose, a small-size neutron detector based on a boron-enriched cast polystyrene scintillator was proposed and developed [2]. The paper presents the results of measuring the boron dose and the dose of γ-radiation in a water phantom and the comparison of these results with the calculated ones.

In BNCT, it is customary to distinguish four components of the absorbed dose: 1) Boron dose due to α-particles and atomic nuclei of lithium – products of the nuclear reaction ^{10}B(n,$\alpha\gamma$)^{7}Li. In the BNCT technique, when boron is accumulated predominantly in tumor cells, the boron dose is therapeutic. 2) The dose of thermal neutrons due to recoil nuclei, mainly protons, of the nuclear reaction of neutron absorption by the atomic nucleus of chlorine ^{35}Cl(n,p)^{35}S and nitrogen ^{14}N(n,p)^{14}C. 3) The dose of fast neutrons due to recoil nuclei during elastic scattering of neutrons on the nuclei of matter. 4) The dose of γ-radiation due to the ionization of atoms of a substance under the influence of γ-radiation. Sources of γ-quantum are a charged particle accelerator, a neutron-generating target, a beam shaping assembly, and an irradiated object (patient).

In the book on neutron capture therapy [1] on page 279 it is written that “the first two components of the dose cannot be measured in principle”. However, for the measurement of the boron dose, a small-sized neutron detector with a cast polystyrene scintillator enriched with boron has been developed [2].

DESIGN OF THE ACCELERATOR

The studies were carried out at the accelerating neutron source of the BINP, constructed for the development of boron neutron capture therapy for malignant tumors [3] (Fig. 1). The neutron source consists of three main units: 1) an electrostatic tandem proton accelerator of an original design (a tandem accelerator with vacuum insulation) to obtain a stationary proton beam with an energy of up to 2.3 MeV and a current of up to 10 mA; 2) a lithium target for generating neutrons in the threshold reaction ^{7}Li(p,n)^{7}Be; and 3) a system for generating a therapeutic neutron beam for forming an epithermal neutron beam for therapy or a thermal neutron beam for research on cell cultures or small laboratory animals.

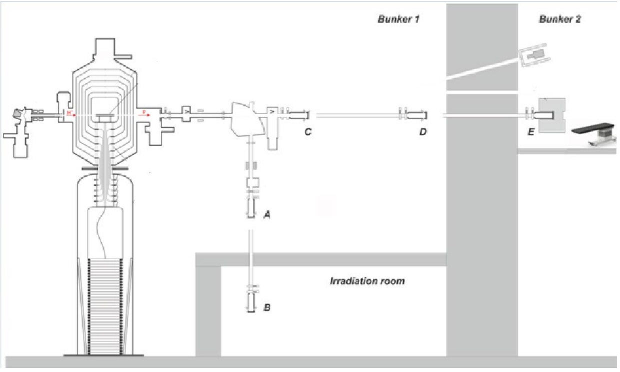

Figure 1: Layout of the experimental facility.

As seen in Fig. 1, the lithium target is placed both in the vertical path (position A) and in the horizontal path (position C) and is planned to be placed in position B for radiation testing of materials with fast neutrons, in position D for boron imaging by the method of instantaneous γ-spectroscopy with a beam monoenergetic neutrons and in position E for clinical trials of the BNCT technique.

In carrying out these studies, preliminary experiments were carried out with the target in position A, the main ones – in position C.

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EXPERIMENTAL RESULTS

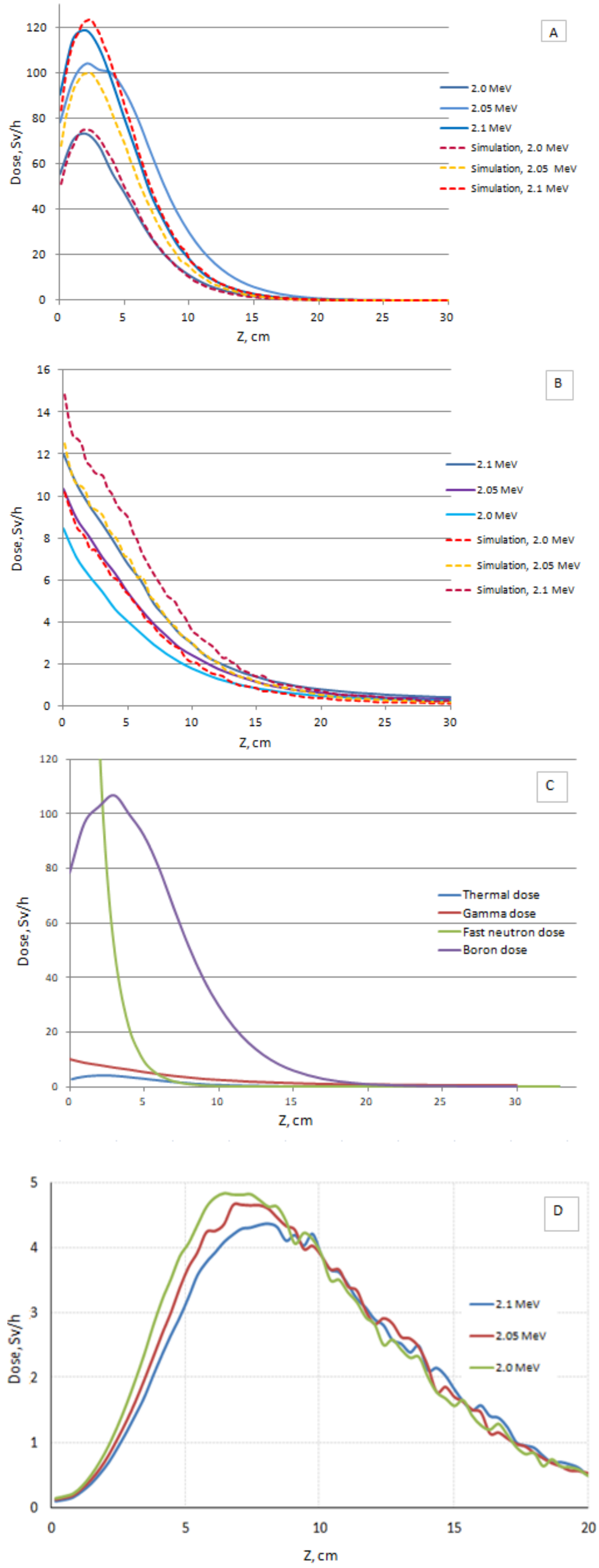

Figure 2: boron dose (a), γ-dose (b), the distribution of all doses along the beam axis (c), the ratio of the "useful" to "harmful" dose (d).

In Fig. 2 shows the dependences of the dose calculated by the detectors on the coordinate along the axis of the proton beam (Z-axis) at three values of the proton energy for: 1) boron dose; 2) γ-ray dose; 3) the ratio of the "useful" to "harmful" dose. On the graphic of the distribution of all doses along the beam axis the data were obtained at an energy of 2.05 MeV. Position $Z = 0$ corresponds to placing the detector close to the phantom input window; in this case, the distance between the lithium layer and the detector is 5cm. During the experiment, the movable carriage traveled a distance from 0 to 30 cm along the Z axis with a step of 1 cm. The boron and gamma dose plots show the calculated data plotted using the NMC code using the Monte-Carlo method. For subsequent doses of thermal and fast neutrons is calculated in the same way.

The dose distribution graph along the beam axis shows a significant difference in the thermal neutron dose and the gamma dose, in contrast to the boron dose, despite their slow decrease along the beam axis. Considering this contribution of thermal neutrons and gamma radiation, as well as a significant drop in the dose of fast neutrons, we can observe an acceptable ratio of the useful dose to the harmful dose at a distance of 8 cm from the lithium target.

From the obtained ratio of the "useful" dose to the "harmful" dose, it can be noted that the ratio at proton beam energy of 2.1 MeV is lower than at 2.0 and 2.05 MeV. Based on the graph, the most acceptable beam generation mode is 2.0 MeV, but a careful study of the distribution of boron dose along the Z axis, one can notice a significant increase in the useful dose in comparison with the threshold proton energy of 2.05 MeV. Based on this consideration, as well as a slight difference in the graphic of all doses distribution, the most effective mode for boron neutron capture therapy was the neutron generation reaction at proton beam energy of 2.05 MeV.

In addition to the distribution along the axis of the epithermal neutrons beam, the contribution of doses in the transverse plane (Y-axis) was also measured. The carriage with the sensors fixed on it was placed in the position of the maximum boron dose along the Z axis, after which the gamma and boron dose were measured in the plane perpendicular to the axis of the epithermal neutron beam. At each point, 120 measurements were made at energies of the proton beam of the accelerator of 2.05 and 2.1 MeV.

From the graphic shown in Fig.3, we can see that the dose distributions perpendicular to the beam axis take a bell-shaped form. Similar to the readings along the beam axis, the calculated and experimental data for the boron dose practically coincide due to the calibration of the conversion factor for simulation by the Monte Carlo method. It is also worth noting the smoother behavior of the experimental gamma dose data compared to the model, as well as a 10 percent difference in readings.

To compare the value of boron dose with doses of gamma radiation, as well as with doses of fast and thermal neutrons, a general distribution graph was plotted perpendicular to the axis of the neutron beam, also shown in Fig. 3. It can be seen from the graph that the distribution of all doses takes the form of a Gaussian function. Of the "harmful" doses, fast neutrons make the greatest contribution, but the function rapidly decreases with displacement from the center of the epithermal neutron beam. On the other hand, the dose from thermal neutrons and gamma radiation is almost an order of magnitude less than the readings of the boron dose, but the half-width of their Gaussian functions is large.

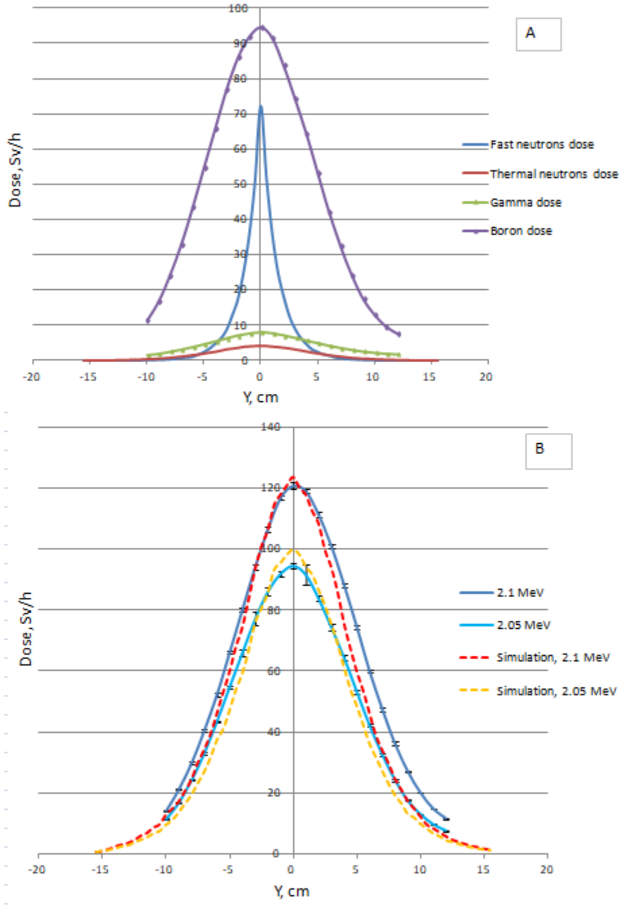

Figure 3: Distribution of doses along the Y-axis: the distribution of all doses (a), the comparison of experimental and calculated data of boron dose (b).

CONCLUSION

In boron neutron capture therapy of malignant tumors, four dose components are distinguished: 1) boron dose, which ensures the destruction of tumor cells due to the selective accumulation of boron in them, 2) a dose of fast neutrons due to elastic scattering of neutrons on atomic nuclei of matter, 3) a dose of thermal neutrons (nitrogen dose) due to $^{14}N(n,p)^{14}C$ reaction and 4) γ-ray dose. The last three doses are non-selective – they damage both tumor cells and healthy tissue cells. The BNCT tends to increase the selective boron dose and decrease the non-selective dose.

The spatial distribution of the boron dose and the γ-ray dose in a water phantom was measured at the accelerator source of epithermal neutrons at the BINP using a specially designed small-size detector with a cast polystyrene scintillator. It was found that the measurement results are in good agreement with the calculated ones. It was shown that at proton energy of 2.05 MeV and a boron concentration in tumor cells of 40 ppm, the selective boron dose is 4 times higher than the sum of non-selective doses, which is acceptable for therapy.

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