NUMERICAL SIMULATION OF NEUTRON FLOW EXPOSURE ON THE ORGANIC TISSUES

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The algorithm of numerically modeling of the impact of the portable neutron generator (PNG) neutron flux on organic tissue is developed and implemented, we used water phantom as a model object. The algorithm for calculating the characteristics of movement and absorption of neutrons and the absorbed dose is based on the Monte Carlo method. It is shown that the main part of the dose is absorbed in the vicinity of the neutron source (at ~1.5…2 cm), this fact makes it possible to effectively treat certain cancers.

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FORMULATION OF THE PROBLEM

One of the major problems facing mankind is the development of effective treatments for cancer. Besides surgical techniques and chemotherapy, irradiation of the tumor is widely used, thus it is a gamma-irradiation, irradiation of protons or neutrons.

Work on the development of methods of neutron irradiation of malignant tumors are maintained, particularly in the US, Russia (Obninsk, Tomsk, Snezhinsk, Novosibirsk) [1 - 7]. Traditionally neutron irradiation is realized through the creation of a neutron beam by the collimation in the presence of a strong neutron source-generator or reactor. This approach requires large attachment means both in constructing the installation and during its maintenance, in particular, to ensure safety of the patient and staff.

An alternative approach to the problem- portable neutron generator, with substantially lower neutron output, while it does not require large investments in the construction (it is much more simple to provide the safety of the installation personnel and of the patient), moreover, the neutron source may be arranged in the vicinity of the patient or within the body of the patient, thus providing a sufficient therapeutic effect for neutron output.

Currently, portable neutron generator (PNG), intended primarily for use in medical applications to treat cancer was designed in KIPT, project STCU P497.

Obviously neutron field in the organic tissue depends on how precisely located neutron source, so it is important to be able to execute the characteristics of the field in all possible positions of the neutron source. In particular, we are talking about cases where the neutron source is located in the immediate vicinity of the tumor, but outside the patient's body (e.g., the treatment of melanoma), and brachytherapy (for example, the treatment of uterine cancer for women and prostate cancer for men) as a source of neutrons surrounded organic tissue on all sides.

A number of software packages for numerical simulation of the interaction of radiation with matter [8 - 10] are actively developed, the development of such packages usually involves a large number of people, software is quite expensive and sometimes difficult to affordable.

Therefore, to solve private task- enough modeling of the neutron behavior in substance (excluding other types of radiation, changes in the composition of matter, nuclear fission, etc.) it seems appropriate to develop an algorithm "from scratch".

An algorithm to assess the effect of the neutron field in the organic tissue (numerically modeling the formation, distribution, braking and neutron absorption), based on the Monte Carlo method, has been developed and implemented.

As a model of tissue we use an approximation of the water phantom. The neutron energy corresponds to the actual energy with which the neutrons leave the target of beryllium (a portable neutron generator neutrons are produced by the interaction of deuterons with beryllium nuclei). In this paper we consider a situation where the neutron source is placed in close proximity to the tumor and is inside the patient's body. This formulation of the problem corresponds, in particular, irradiation of prostate cancer in men and uterine tumors in women.

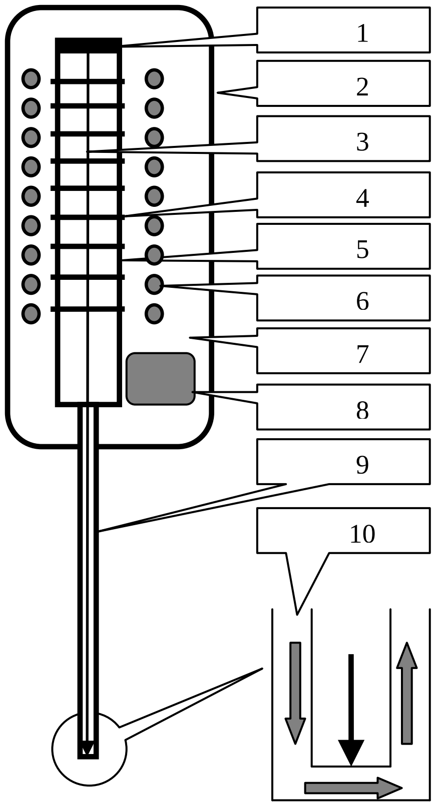

Fig. 1. General scheme of PNG:
1 – Source of deuterons; 2 – Accelerator casing; 3 – Beam of deuterons; 4 – Accelerator electrodes; 5 – Vacuum tube; 6 – Gradient rings; 7 – Elegas, sulfur hexafluoride; 8 – Vacuum pump; 9 – Needle-ion pipe; 10 – Fluid of water in target cooling system.
Fluid of water in target cooling system

Let us dwell on the construction of PNG (Fig. 1). Neutron appears in beryllium target, resulting in an interaction of deuterons with beryllium nuclei after the accelerator deuterons pass through a narrow ion transport "needle", "needle" can be entered into the patient's body (as already mentioned above, we are talking about prostate cancer for men and cancer of the uterus for women).

In order to estimate the absorbed dose in the organic tissue will consider the model situation: there is a point source of neutrons with an average energy of about 2.5 MeV (which corresponds to the energy source of neutrons in the reaction $^2H + ^9Be \rightarrow ^{10}B + n$; if the target is made of lithium, the reaction $^2H + ^7Li \rightarrow ^8Be + n$, $^2H + ^7Li \rightarrow 2\,^4He + n$, the initial energy of the neutrons will be significantly more), located in the center of the water phantom measuring 20×20×20 cm.

NUMERICAL REALIZATION

The algorithm of interaction modeling of neutrons with the nucleus is built taking into account the fact that it is the interaction of the neutron with light nuclei. The algorithm is based on the following assumptions.

The basic mechanism of interaction of the nuclei of oxygen and hydrogen neutrons is elastic interaction.

The trajectory of the neutron is tracked to the point where it:

a) leaves the phantom or;

b) is absorbed by the nucleus of hydrogen or oxygen nucleus.

The cross sections for the scattering and absorption of neutrons in the nuclei taken from the database [11].

Oxygen and hydrogen nuclei oscillate according to the temperature of the phantom (T~ 300°K, k is Boltzmann's constant), each degree of freedom corresponds to energy kT/2. It should be noted that at low neutron energies of a few electron-volt in modeling the interaction of a neutron the binding energy of nuclei in molecules must be considered, but this value has little effect on the absorbed dose, as main dose absorbed at much higher neutron energies.

The need to keep track of the interaction of thermal and epithermal neutrons from the nuclei of the organic tissue can occur in the modeling process of boron neutron capture therapy.

We use the notation:

A – the number of nucleons in the nucleus;

M, V – mass and velocity of nucleus (sign vector omitted to simplify the formulas);

m, v – neutron mass and velocity;

v_c – the velocity of the center of mass of the neutron + nucleus;

V_t – thermal velocity of the nucleus;

n – unit vector in the direction of the velocity of the neutron;

sign «’» means variables (velocity, velocity components, energy) in CMS;

E – system energy before interaction, eV;

E_0 – neutron energy before interaction, eV;

kT/2 – thermal energy per one degree of freedom, eV;

$\theta \in [0;1]$ – random value, which determines thermal energy;

R random value, R=+1 or R=-1 with equal probability,

$\varepsilon_x = \frac{v_{tx}}{v_{0x}} = \sqrt{\frac{1}{2}\frac{1}{A}\frac{kT}{E}}\theta n_x^{-1}$ – ratio of x-component of nucleus thermal velocity in LCS before interaction, definitions ε_0 are analogues.

Let’s consider the interaction of the neutron with the nucleus.

Obviously, the energy of the center of mass can be expressed in the form (all variables in formula are before the interaction of the neutron with the nucleus).

$$E' = \frac{m}{2}\left[\left(v_x - v_{cx}\right)^2 + \left(v_y - v_{cy}\right)^2 + \left(v_z - v_{cz}\right)^2\right] + \\ + \frac{M}{2}\left[\left(V_{tx} - v_{cx}\right)^2 + \left(V_{ty} - v_{cy}\right)^2 + \left(V_{tz} - v_{cz}\right)^2\right]. \quad (1)$$

In our notation, after identity transformations we obtain:

$$\frac{E'}{E} = 1 + \theta - 2n_x^2\frac{1+A\varepsilon_x}{1+A} - 2n_y^2\frac{1+A\varepsilon_y}{1+A} \\ - 2n_z^2\frac{1+A\varepsilon_z}{1+A} + \quad (2) \\ + A\begin{pmatrix} n_x^2\varepsilon_x^2 + n_y^2\varepsilon_y^2 + n_z^2\varepsilon_z^2 - 2\varepsilon_x n_x\frac{1+A\varepsilon_x}{1+A} - \\ - 2\varepsilon_y n_y\frac{1+A\varepsilon_y}{1+A} - 2\varepsilon_z n_z\frac{1+A\varepsilon_z}{1+A} \end{pmatrix}$$

$$\theta = \left(\frac{1}{1+A}\right)^2\begin{bmatrix} n_x^2\left(1+A\varepsilon_x\right)^2 + n_y^2\left(1+A\varepsilon_y\right)^2 + \\ + n_z^2\left(1+A\varepsilon_z\right)^2 \end{bmatrix}.$$

The interaction of the neutron with the nucleus takes place with laws of conservation of momentum and energy.

In CMS after the interaction, we write:

$$MV' = mv', \quad (3)$$

$$\frac{MV'^2}{2} + \frac{mv'^2}{2} = \phi E_0.$$

Note that in last equation it easy to take into account the exothermic reaction or endothermicity adding one term in the right-hand side of the second equation.

The components of the neutron velocity after interaction with the nucleus in the laboratory coordinate system are:

$$v_x = \sqrt{\frac{2A}{A+1}\phi\frac{E_0}{m}}n_x' + v_{cx}, \quad (4)$$

$$v_y = \sqrt{\frac{2A}{A+1}\phi\frac{E_0}{m}}n_y' + v_{cy},$$

$$v_z = \sqrt{\frac{2A}{A+1}\phi\frac{E_0}{m}}n_z' + v_{cz}.$$

n' – vector components of the unit vector defining the direction of the neutron velocity after interaction with the nucleus in CMS are determined randomly.

On the basis of last equations is easy to calculate the neutron energy after the interaction with the nucleus and the values of the components of the unit vector n, which determines the direction of the neutron velocity after interaction in the LCS.

We formulate the main elements of the algorithm modeling the interaction of neutrons with matter. Suppose that a neutron moves with velocity v, the unit vector determining the direction of movement n.

The movement of the neutron is considered over the interval L (choose L << max $(1/N_i\ \sigma_i)$, i = 1, 2, 3, 4). Indices correspond to cross- sections for scattering on nuclei of hydrogen and oxygen, absorption by the nuclei of hydrogen and oxygen, Ni – density of the corresponding nuclei.

During the interval may L neutron can:

a) change and dissipate energy and speed;

b) absorb;

c) go beyond the computational domain.

What exactly will be- randomly determined, situation is based on the information on the cross sections of the nuclei and the concentration of oxygen and hydrogen [11].

If there was a scattering process, lost the neutron energy is considered a contribution to dose substance.

If there was no neutron absorption or going beyond the computational domain, the process of tracking the neutron is similar.

Considered numerical algorithm is implemented in a computer program.

As a test the length of neutrons in the water calculated.

The program provides 5.1 cm, reference data [12, 13] – 5.14 cm.

ADSORBED DOSE EVALUATION FOR PNG OPERATION

Results of adsorbed dose estimation in water phantom are shown on Fig. 2, neutron output in PNG W ~ 10^9 neutron/s.

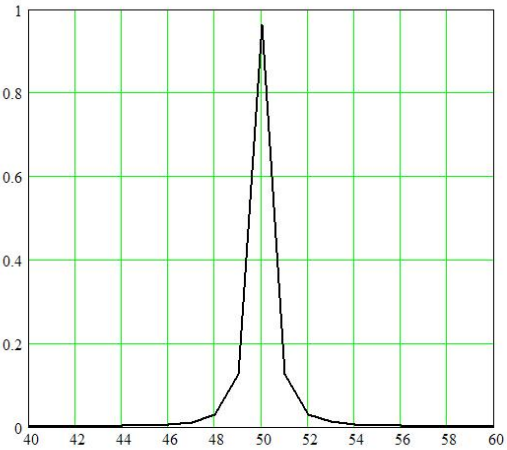

Fig. 2. Adsorbed dose (rel. units.) as a function of direction from single neutron source (rel. units)

The neutron source PNG is actually a portion of the surface perpendicular to the axis Z, the size of about 1 cm.

The dose distribution along the Y-axis in this case is shown in Fig. 3.

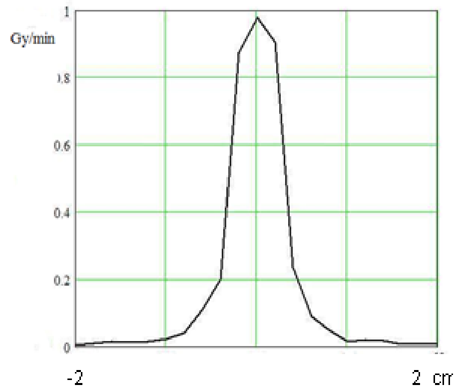

Fig. 3. The dose distribution along the Y axis in the ion source of finite size

One may indirectly check the calculation results as follows. The neutron energy is absorbed mainly at distances R ~ 2 cm from the source.

Evaluation of dose absorbed in the specified area will be (E_0 initial energy neutrons, W- neutron output):

$$D \approx \frac{WE_0}{\frac{4}{3}\pi R^3} \approx 0.3\frac{Gy}{\min}.$$

This corresponds to numerical execution results Fig. 3.

RESULTS AND DISCUSSION

Algorithm of formation, distribution and absorption of neutrons in the water phantom, based on the Monte Carlo method, designed and implemented by numerically modeling, it corresponds to the modeling of the impact of the neutron flux portable neutron generator on organic tissue.

It is shown that the primary dose is absorbed at small distances from the neutron source (1.5…2 cm), thereby providing a sufficient therapeutic effect on neutron flux tumor.

An analytical evaluation of the absorbed dose proposed, the result is close to the characteristic values of the dose calculated by the Monte Carlo method.

The absorbed dose of neutrons is localized in the vicinity of the source and decreases rapidly with distance, this fact is extremely important in terms of practical PNG use in radiation medicine- on can affect the diseased cells of the body and do not touch with the healthy tissue. That is why an important element of PNG is ion "needle" [5], thanks to the "needle" in many cases one can place neutron source in close proximity to the tumor without surgery.

CONCLUSIONS

We have developed a program to estimate the dose absorbed by the organic tissue as a result of exposure to neutrons. We take into account that the human body is composed mainly of water molecules, so the simulation is carried out on a water phantom.

The proposed approach to assessing the impact of the neutron flux in the organic tissue permits to evaluate the real value of the dose depending on the location of the neutron source, and therefore – to evaluate the effectiveness of cancer treatment.

In this paper, we consider a situation where the source is located inside the patient's body, the source of such an arrangement is realized thanks to design PNG features (in the first place – the presence of a narrow ion guide – the "needle").

It is interesting to study the possibility of using PNG for tumors located on the surface of the body (melanoma), modeling the interaction of neutron flux with organic tissue, in this case – one of the challenges currently faced by the authors.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВОЗДЕЙСТВИЯ НЕЙТРОННОГО ПОТОКА НА ОРГАНИЧЕСКУЮ ТКАНЬ

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Разработан и численно реализован алгоритм моделирования воздействия нейтронного потока портативного нейтронного генератора (ПНГ) на органическую ткань. В качестве модельного объекта воздействия использован водяной фантом. Алгоритм расчета характеристик движения и поглощения нейтронов и поглощенной дозы основан на методе Монте-Карло. Показано, что основная часть дозы поглощается в непосредственной близости от источника нейтронов (на расстоянии ~1,5…2 см), что дает возможность эффективно проводить лечение некоторых онкологических заболеваний.

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Розроблено та чисельно реалізовано алгоритм моделювання впливу нейтронного струму портативного нейтронного генератора (ПНГ) на органічну тканину. В якості модельного об’єкта впливу обрано водяний фантом. Алгоритм обчислення характеристик руху та поглинання нейтронів заснований на методі Монте-Карло. Показано, що основна частина дози поглинається в безпосередній близькості до джерела нейтронів (на відстані ~1,5…2 см), що дає можливість ефективно проводити лікування деяких онкологічних захворювань.