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A virtual model of the patient's head for BNCT

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The aim of the present work was creating a virtual phantom of a human head for BNCT, as a part of the BNCT programme project. This model is an amplification of the simple model described in earlier publications. It takes into account the major head organs as well as the scalp and skull. The chemical composition of all tissues was modelled according to the recommendations of the ICRP. The organs were parameterized using mathematical formulas based on the human head magnetic resonance images. The model was used for calculating the thermal neutron flux and the injuring (fast neutron, nitrogen and gamma) dose components for the head irradiated using the therapeutic neutron beam, whose parameters were obtained as the result of the modelling of the filter/moderator system for the BNCT therapeutic beam from the MARIA reactor.

Key words: BNCT, Boron Neutron Capture Therapy.

Introduction

Boron neutron capture therapy (BNCT) is an experimental therapy which brings together two components that, when kept separate, have only minor effects on cells. The first component is a stable isotope of boron (boron-10) that can be concentrated in tumour cells by being attached to tumour-seeking compounds. The second one is a beam of low-energy neutrons. Boron-10 in or adjacent to tumour cells disintegrates after capturing a neutron. The high-energy, heavy charged particles produced destroy only those cells, primarily cancer cells, which are in close proximity to the vertex, leaving adjacent normal cells largely unaffected.

The BNCT research programme started in Poland in 2001. The MARIA reactor in Swierk is to be used as a source of epithermal neutrons for the BNCT irradiation facility, which will be placed at one of seven horizontal neutron beam channels of the reactor (channel H2).

A flux of the epithermal neutrons from the reactor MARIA is too low to be directly used for BNCT treatment. Therefore it was necessary to place a fission converter between the reactor core and the BNCT irradiation port. The uranium converter will be placed in the reactor pool, near the front of the H2 channel. The neutron beam will then be moderated and filtered, in order to reach the intensity, composition and energy spectrum fulfilling therapeutic requirements.

The aim of the present work was to create a virtual phantom of a human head for BNCT, as part of the project concerning the optimization of the spectrum and collimation degree of the BNCT beam. At present, the phantom will be used in numerical modelling for a converter/filter/moderator system design [2] and for calculations of the neutron transport in the human head. In the future, it will also be possible to calculate the absorbed dose in the patient's head during a BNCT therapeutic session, provided that the parameters of the neutron beam from the MARIA reactor and passing through the converter and filter/moderator system are known.

The mathematical model of the human head presented in this article is an amplification of the simple model described in our earlier publications [3, 4]. The previous model was defined using the MCNP code as a 20-cm diameter sphere of tissue-like homogeneous material (ICRU brain) consisting of hydrogen (10.7%), carbon (14.5%), nitrogen (2.2%), oxygen (71.2%), sodium (0.2%), phosphorus (0.4%), sulphur (0.2%), chlorine (0.3%) and potassium (0.3%) of the density of 1.04 g/cm^3. The sphere was divided into 60 pieces of various sizes: 6 layers of concentric, cylindrical cells up to the depth of 7 cm, and the rest of the head was defined as one cell. The absorbed dose calculations were carried out using a monoenergetic neutron beams with energies between 1 eV and 1 MeV.

The model was used for the testing of mathematical methods and for rough calculation of the optimum neutron beam energy for therapeutic purposes, but it was too simple for more complicated calculations (i.e. therapy planning). Therefore, a more realistic model was developed, based on MRI (magnetic resonance) images of the human head. The MR modality was chosen because these images are associated with the content of protons in tissues, while the hydrogen content is crucial also for a number of neutron interactions in tissue.

Method

The new virtual model takes into account the major head organs such as the left and right cerebral hemispheres, cerebellum and eyes. It includes the scalp and skull as well. The other organs that do not affect the dose distribution were neglected. The chemical composition of all tissues was modelled according to the recommendations of the ICRP [1]. The space surrounding the organs inside the skull was defined as that filled with 'soft tissue'.

The organs were parameterized using mathematical formulas based on the human head magnetic resonance images. Twenty five MR images were used in order to calculate the organs' dimensions and positions and to determine equations describing the surfaces of the organs.

These equations are presented below:

The shape of the skin layer (the external layer of the head) is described as an elliptical cylinder:

$$\frac{x^2}{94^2}+\frac{y^2}{83^2}=1$$

covered on the top with a sphere:

$$x^2+y^2+(z-25)y^2=113^2.$$

The inner layer of the skin and the external layer of the skull is an elliptical cylinder:

$$\frac{x^2}{(92.5)^2}+\frac{y^2}{80^2}=1,$$

covered on top with a sphere:

$$x^2+y^2+(z-22)y^2=113^2.$$

The external layer of the skull is an elliptical cylinder:

$$\frac{x^2}{84^2}+\frac{y^2}{72^2}=1,$$

Figure 1. The virtual model of the head. In the picture on the right, the skin and skull layers are transparent, as well as the 'soft tissue' layer filling the head phantom.

covered on top with a sphere:

$$x^2 + y^2 + (z - 14)y^2 = 113^2.$$

The left and right cerebral hemispheres are the sums of two ellipsoids:

$$\frac{x^2}{(81.5)^2} + \frac{(y \pm 10.5)^2}{(55.5)^2} + \frac{(z - 76)^2}{48^2} = 1.$$

The cerebellum is the sum of two ellipsoids:

$$\frac{(x + 44.5)^2}{25^2} + \frac{(y \pm 23)^2}{23^2} + \frac{(z - 37)^2}{(18.5)^2} = 1.$$

The eyes are two ellipsoids:

$$\frac{(x - 59)^2}{(13.5)^2} + \frac{(y \pm 28)^2}{16^2} + \frac{(z - 15.9)^2}{(15.9)^2} = 1.$$

The eye sockets are two ellipsoids:

$$\frac{(x - 70)^2}{(27.5)^2} + \frac{(y \pm 28)^2}{20^2} + \frac{(z - 15.9)^2}{20^2} = 1.$$

The visualisation of the virtual model of the human head is presented in Figure 1.

Calculations

The dose absorbed by the tissue in BNCT consists of four components:

1. The gamma ray dose from the gamma ray component of the beam and the gamma rays induced in the tissue, mainly due to $^{1}H(n, \gamma)^{2}H$ reactions emitting 2.2 MeV gamma rays.
2. The fast neutron dose epithermal and fast neutrons that cause 'knock-out' recoil protons from hydrogen in tissue.
3. The nitrogen dose from ^{14}N absorbing a thermal neutron and emitting 0.6 MeV a proton in $^{14}N(n,p)^{14}C$ reaction.
4. The boron dose from 10B absorbing a thermal neutron in a $^{10}B(n, \alpha)^{7}Li$ reaction. The emitted α particle and the recoiling ^{7}Li ion result in locally-deposited energy, averaging about 2.34 MeV. In 94% of the reactions, the recoiling ^{7}Li ion is produced in an excited state, and de-excites, emitting a 477 keV gamma ray. In the remaining 6% of events, a ^{7}Li ion is emitted in the ground state.

In order to calculate the dose absorbed in various parts of a particular organ, the head was divided into voxels of 1×1×1 cm size. It is possible to calculate a neutron flux or a number of reactions caused by neutrons in each particular voxel.

Unfortunately, the geometry of the head is too complicated for the MCNP code to calculate the volumes of the cells explicitly and the voxels containing the fringes of the head organs, where one voxel contains parts of different organs (Figure 2). In such a

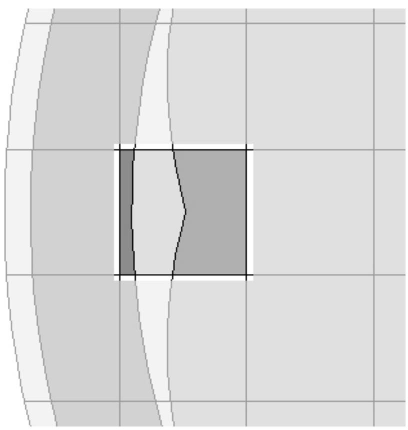

Figure 2. An example of a voxel whose parts belong to different organs – the skull, soft tissue and the brain.

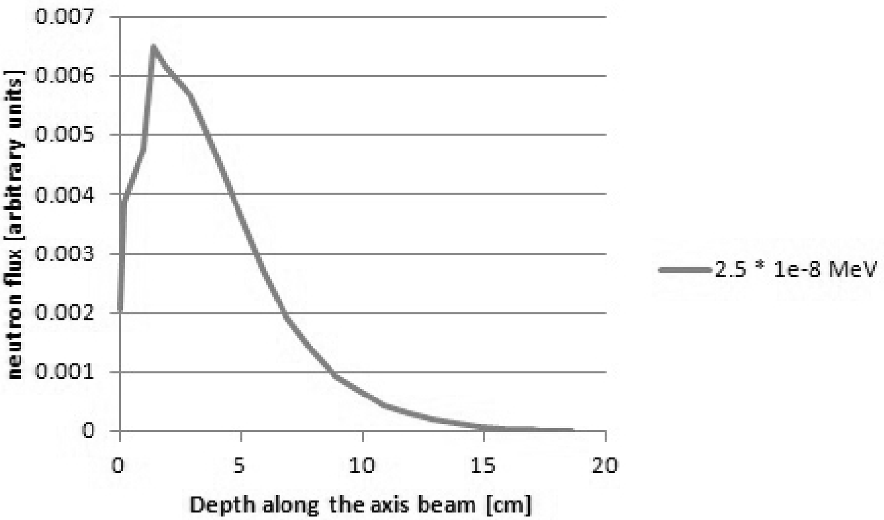

Figure 3. The thermal neutron flux in the human head as a function of the depth along the beam axis. The model takes into account the thickness of the skin (0-2 mm), the skull (2-10 mm), soft tissue (10-15 mm) and the brain.

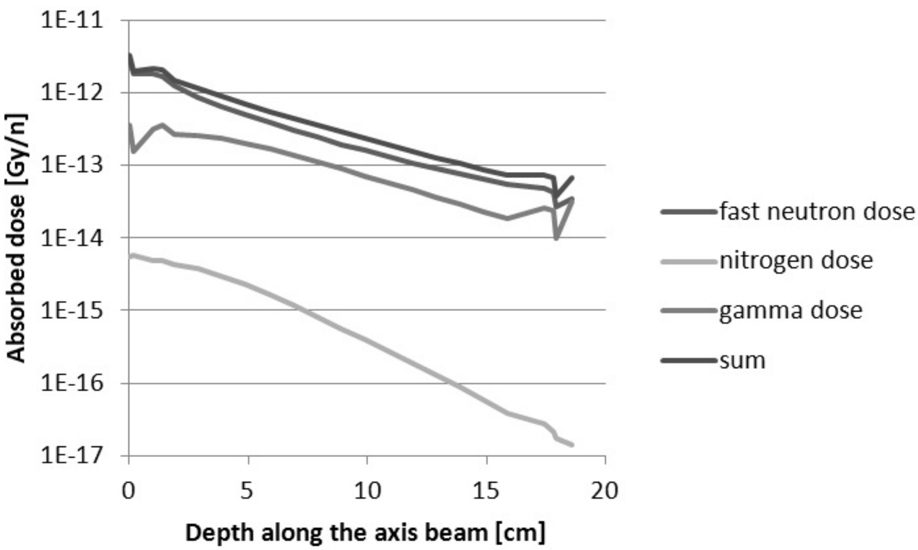

Figure 4. The dose absorbed in the human head as a function of the depth along the beam axis. The model takes into account the thickness of the skin (0-2 mm), the skull (2-10 mm), soft tissue (10-15 mm) and the brain. Differences in the dose absorbed in various tissues can easily be seen.

case, the values of calculations based on the track length (MCNP: f4 type tally) have improper normalization, because the MCNP code for each of the fragments assumes a volume equal to the volume of the whole voxel.

One of the methods to obtain proper normalization of the fringe voxels is to use the same geometry of the head, but with a void instead of tissue, with the neutron beam aiming at the voxel (group of voxels) to be normalized. The neutron flux should be constant and equal to 1 for f4 type tally for all the voxels on the beam axis, but in the problematic voxels it is equal to the fraction of the voxel volume belonging to a particular organ, so that the calculated value may be used for analyzing the non-void calculations.

The model was used for calculating the thermal neutron flux and the injuring (fast neutron, nitrogen and gamma) dose components for the head irradiated using the therapeutic neutron beam, whose parameters were obtained as the result of the modelling of the filter/moderator system for the BNCT therapeutic beam from the MARIA reactor, described in [5]. The results are presented in Figures 3 and 4.

Conclusions

The created model of the patient's head is more universal than the spherical one described in [3, 4] because it models the most important head organs and can be used for various geometries and beams emitted from different directions and angles.

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