Design of a new neutron filter for Boron Neutron Capture Therapy

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Introduction

The idea of Boron Neutron Capture Therapy (BNCT) is to destroy brain-tumour cells by doping them with boron-rich molecules followed by neutron irradiation. The energy released after the neutron capture interaction kills the tumour cell.
The isotope ^{10}B has very good abilities for capturing thermal neutrons, followed by an instantaneous disintegration into two particles: a helium and a lithium nucleus. These nuclei have kinetic energies of about 2.5 MeV and a very short stopping range in tissue of about 10 μm [$^{10}B(n,\alpha)^{7}Li$]. Such reactions, when produced selectively in tumour cells, open an effective new modality for cancer treatment. The first clinical trial in Europe of BNCT for the treatment of certain brain tumours (glioblastoma) started in October 1997 at the High Flux Reactor (HFR) in Petten. For most of the BNCT facilities in the world, an epithermal neutron beam is used with an average energy of around 10keV. In human tissue, containing ^{10}B compounds, the beam produces effectively four main dose components, all with different biological effectiveness: the boron neutron capture absorbed dose, the nitrogen neutron capture absorbed dose, the proton recoil absorbed dose and the gamma ray absorbed dose. The last one is a composition of the gamma rays already present in the beam and the induced gamma rays by the presence of hydrogen in human tissue.

New neutron filter

To obtain a beam of 10-keV neutrons, a neutron filter is installed between the core of the nuclear reactor and the patient. The present filter consists mainly of liquid argon (cooled to 85K), which has the ability to allow the transfer of the already epi-thermal neutrons and to reduce the energy, by scatter, of fast neutrons. Due to the other filter materials present, slow neutrons and gamma rays from the reactor core are filtered out as much as possible. Although the filter works perfectly, as proven during the last trial, the problem is the maintenance of the system to cool the argon. In addition, the question arose whether it is possible to optimise the beam characteristics for every specific tumour size and position. Furthermore, the present interest to use BNCT for other kinds of cancer treatments, such as extra-corporal organs, like the liver, need different neutron characteristics like energy and flux density.

The four dose components

The first step in trying to improve the neutron beam is to investigate if variation of the source neutron energy can influence the treatment favourably. It can be postulated that the optimal source neutron energy, which is the energy that delivers most of the alpha reactions in the tumour without exceeding dose limits set for healthy tissue, depends on the position of the tumour. For this purpose, as a first step, in MCNP [1],

a cubic head phantom is modelled with skin (5 mm), cranium (9 mm) and brain and irradiated with different source neutron energies. The centre of a spherical tumour (ø4 cm) is positioned in the brain 4 cm from the skin. The tumour differs only from the normal tissue because it contains 30 ppm of ^{10}B instead of 10 ppm as present in the other tissues. Figure 1 shows four plots representing the secondary particles, produced per cubic centimetre in the phantom and per source neutron, which are causing the four typical BNCT dose contributors.

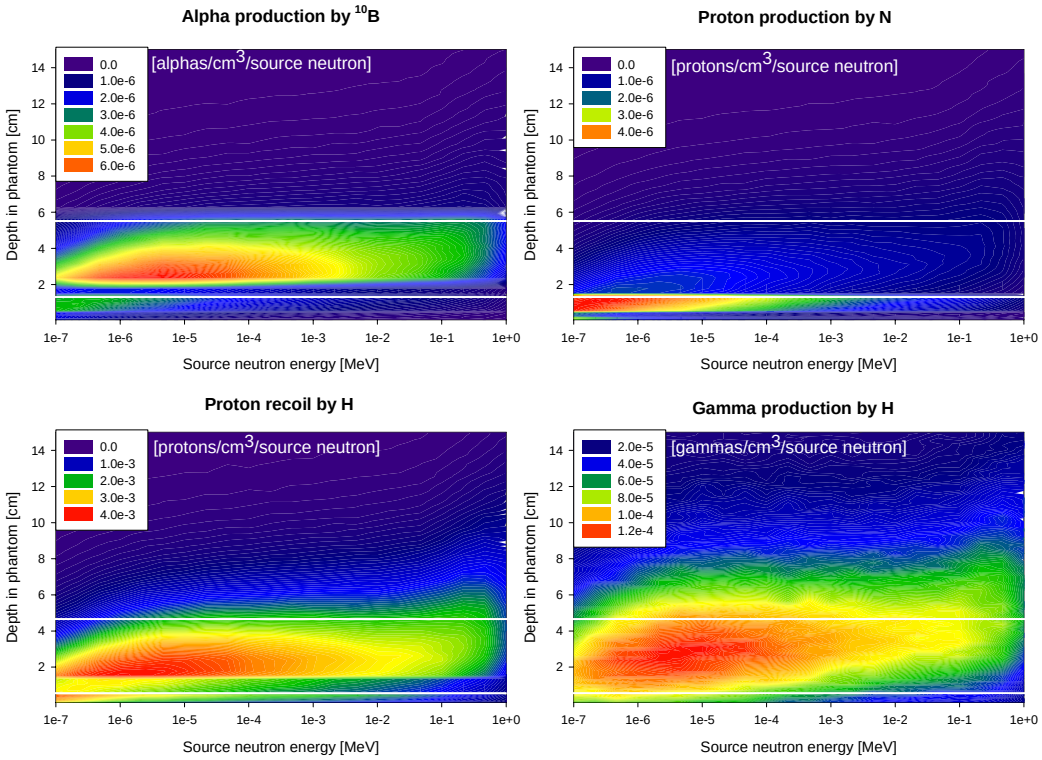

Figure 1. Results for the produced secondary particles in a cubic head phantom in BNCT. Below the lower white lines, the cranium and skin are located, between the white lines the tumour tissue, and above the upper white line healthy brain tissue.

Figure 1 gives an insight into what is happening in the head during irradiation with source neutrons of different energies ranging from 0.1eV to 1MeV. It can be seen that the lower source neutron energies produce a lot of alpha particles in the tumour, as well as producing a significant amount in the cranium. The produced protons and gamma rays are independent of the position of the tumour and show a decreasing number of particles per cubic centimetre with increasing source neutron energy. This suggests the use of higher source neutron energies, but after translating these productions into absorbed doses it becomes clear that the proton recoil dose increases rapidly for higher source neutron energies. These facts illustrate that the optimal source neutron energy is nothing more than searching for a compromise.
Since medical doctors are interested in a measure for the human tissue damage due to the irradiation, the four absorbed doses have to be

multiplied with biological weighting factors in order that they become normalised and can be added. There is however no general agreement on these biological factors, which may vary for several reasons. To circumvent the discussions and the variability, all possibilities have been studied. For all possibilities, the four BNCT dose contributions are added and the optimal source neutron energy is determined. The final result of this study is that the new BNCT neutron filter should deliver neutrons of a few keV, as in its current configuration, but should also include the possibility to deliver around 100 eV. When this is the case, for tumours at all depths and for all imaginable biological factor possibilities, the highest probability to kill the cancer cells is ensured.

Future plans

For the study of the optimal source neutron energy study, at a certain stage, the adjoint Monte-Carlo calculation, which literally calculates backwards from the tumour to the source, can determine which neutron characteristics (for instance, the source neutron angle) are needed to optimally irradiate a patient. The optimal irradiation source characteristics are subsequently calculated. This approach can be promising for other types of radiotherapy as well.

An already existing method has to be improved, which enables to select and fine-tune the characteristics of filter materials. Again the adjoint technique can be helpful in determining in an efficient way if the spectrum after filtering improves after certain adjustments.

[1] J. F. Briesmeister, Ed.: "MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C," LA-13709-M (April **2000**).