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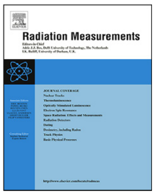

Angular distribution of neutron spectral fluence around phantom irradiated with high energy protons

Z. Vykydal [a], [*], M. Králík [a], J. Šolc [a], J. Vilímovský [b], V. Vondráček [b]

[a] Czech Metrology Institute, Okružní 31, 638 00, Brno, Czech Republic
[b] Proton Therapy Center Praha, Budínova 1a, 180 00, Praha 8, Czech Republic

HIGHLIGHTS

- Extended Bonner spheres spectrometer was used for measurement at proton therapy.
- Experimental conditions were optimized for reliable data acquisition.
- Angular distributions of neutron spectral fluence around the phantom were measured.
- Technique for the neutron spectral fluence benchmarking was proposed.

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ABSTRACT

Extended Bonner Spheres spectrometer was used to measure the angular distribution of neutron spectral fluence around NYLON6 phantom irradiated with pencil beam of 100, 150 and 200 MeV protons at the Proton Therapy Center Praha. Measurements were supplemented by a calculation of neutron spectral fluences at different depths of the phantom. The calculation of neutron spectral fluence at different depth of the phantom demonstrated that the majority of high energy neutrons was generated at the beginning of the proton trajectory in the phantom and the neutron yield decreased with increasing depth, with a minimum at the depth corresponding to the Bragg peak. Therefore, attention should be paid not only to the tissue behind the irradiated volume, but also to the preceding tissue. However, the neutron spectral fluence in the vicinity of the treated tissue can only be determined by calculation, mainly due to the dimensions of the neutron spectroscopic instrumentation. This paper presents a suitable technique and experimental conditions to acquire reliable data necessary for the proper determination of neutron spectral fluence. From the measured spectral fluences, the neutron fluence in whole-range and partial energy intervals were determined together with the corresponding ambient dose equivalents at measurement positions. The obtained results indicate that high energy neutrons predominate at the direction of the proton beam and more neutrons are generated by higher energy protons.

1. Introduction

Radiotherapy with high energy photons, i.e. with energies above 10 MeV, and hadrons, e.g. protons, carbon ions or other, is always accompanied by unwanted secondary particles, in particular by neutrons. Radiobiological efficiency of neutrons strongly depends on their energy. Therefore, it is essential to know their spectral fluence (spectrum) to assess the impact on the treated and surrounding tissues.

In irradiations with high energy photons, the source of neutrons is a machine – linac itself, particularly the elements of gantry forming the photon beam (Králík et al., 2015). In the case of hadron therapy, the irradiation with secondary neutrons is more complicated because the sources of neutrons are both machine and the irradiated tissue itself. The amount of neutrons generated in the machine depends on the beam modulation technique used to irradiate the specified volume. There are two main techniques – passive (broad) beam delivery and active (pencil) beam scanning. When passive beam delivery is applied, the proton pencil beam passes through the degrader, where the energy of protons is fixed, then it travels through the first scatterer, where the beam profile is enlarged, goes on to the range modulator and optionally to the

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[*] Corresponding author.
E-mail address: zvykydal@cmi.cz (Z. Vykydal).

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second scatterer. The final formation of the beam profile is done with a collimator (usually made of brass) and a range compensator. The parts located inside the nozzle are sources of unwanted neutrons hazardous to the patient. During active beam scanning, proton pencil beam passes through the degrader and then through the magnetic scanner, which distributes it over the irradiated volume. Compared to passive beam delivery, in the active mode the beam of protons or ions does not pass through a heavy material inside the nozzle and thus the number of unwanted neutrons is significantly reduced (Farah et al., 2015).

The measurements were carried out at the Proton Therapy Center Praha (PTC), Czech Republic, where active beam scanning is routinely used. In this method, it is more important to assess the risks from neutrons generated in the patient body than the risks from external irradiation with neutrons. In order to find a suitable technique and experimental conditions to acquire reliable data necessary for the proper determination of neutron spectral fluence, we decided to measure angular distribution of this quantity around the cylindrical phantom whose front face was irradiated with a pencil beam of protons with different energies. This simple arrangement was chosen to avoid problems with the interpretation of the measured neutron spectral fluence, which is influenced by neutron generation and transport inside of the phantom. The spectral fluence was measured by means of the Extended Bonner Spheres spectrometer (EBS) at 1 m distance from the iso-centre under six different angles from 0° (direction of the proton beam) up to 120°. Neutron spectral fluences at the measurement positions were converted to ambient dose equivalents. All the measured spectral fluences and derived ambient dose equivalents are normalized to the number of impinging protons to allow a simple comparison with the calculations. The measurements are supplemented with the calculation of neutron spectral fluence at different depth of the phantom.

2. Material and methods

2.1. Cyclotron

An isochronous cyclotron C235 of the company IBA S.A., Belgium, is installed at the Proton Therapy Center Praha (PTC). The beam of protons is guided through the beam line to the nozzles, which are the final beam delivering component. The nozzles are placed in four treatment rooms – one with a fixed beam nozzle and three gantry treatment rooms, where the nozzle can rotate 360° around the iso-centre. The degrader, i.e. rotating, variable thickness graphite cylinder, is used to transform the 230 MeV fixed energy proton beam exiting the cyclotron into a beam having the energy in the interval (70, 230) MeV. Proton current at the nozzle can be changed in the interval (1, 300) nA (IBA S.A, 2012).

The accelerating electric field is alternating and its frequency is approximately 106 MHz. The beam is delivered continuously or in the macro pulse regime. All presented measurements were done with continuously delivered beam. The frequency of the accelerating electric field is sufficiently high, so for the purpose of our measurements, it is possible to consider the beam current constant.

The cyclotron operates in two modes, clinical and service. In the clinical mode, the preset dose is delivered within a short time interval (a few minutes), so this mode is not suitable for measurements with active detectors. In the service mode, however, it is possible to run a continuous current of protons with a certain limitation caused by the fact that the cyclotron occasionally stabilizes the beamline parameters and interrupts the beam. This behaviour makes collecting pulses with the active detector in a fixed time interval unreliable making it necessary to relate the number of the registered pulses to the monitor reading.

The current of the delivered protons was monitored with the built-in ionization chamber in the so called monitor units (MUs). The calibration parameters of the chamber are fixed in the way that 1 MU corresponds to the charge of 3 nC generated by the passing protons. Because the charge generated in the ionization chamber depends on the energy of protons, the information about MUs has to be always appended with the energy of protons. 1 MU corresponds to 1.630E+8, 2.178E+8 and 2.650E+8 protons with energies 100 MeV, 150 MeV and 200 MeV, respectively.

The MUs can also be related to the dose measured in a relatively flat region (plateau) in the water phantom at the depth of 2 cm at reference conditions, i.e. the irradiated area of 10 cm × 10 cm covered by 51 × 51 spots (sigma 4–8 mm depending on energy). For proton energies of 100 MeV, 150 MeV and 200 MeV, the corresponding reference doses are 1.12 mGy, 1.10 mGy and 1.10 mGy at plateau, and 3.16 mGy, 3.94 mGy and 4.08 mGy at the Bragg peak. Doses at the depth of 2 cm were obtained during calibrations of the treatment planning system and the doses at the Bragg peak were derived from the measured depth dose curves.

2.2. Extended Bonner sphere spectrometer (EBS)

The Bonner Sphere spectrometer (BS), firstly described by Bramblett et al. (1960), is an instrument that enables measurement of neutron spectral fluence in a wide energy interval. The limitation of the original BS version is in its inability to provide spectrometric information for neutron energies above 20 MeV, where the response functions of individual spheres become linearly dependent and rather low. To overcome these limitations, Wiegel and Alevra (2002) designed the so-called Extended BS, in which the response functions above 20 MeV were changed by adding layers of heavy materials, such as tungsten, lead and copper, to the polyethylene moderators. This idea, which originated in the work of Birattari et al. (1990), was implemented in various other designs of the EBS, e.g. (Mares and Schraube, 1998; Caresana et al., 2007; Bedogni et al., 2014; Howell and Burgett, 2014).

For the measurement of neutron spectra at the PTC Praha, the used EBS consisted of a set of polyethylene moderators with the diameters of 3, 3.5, 4, 4.5, 5, 6, 7, 8, 10 and 12, traditionally given in inches (1 inch = 2.54 cm), produced by CENTRONIC, UK. This set was designed at PTB for SP9 ^{3}He proportional detector (Wiegel et al., 1994). To this set, three spheres, made by the LYNAX s. r. o., Czech Republic, were added:

- 7W – a sphere with the external diameter of 7 inches, consisting of a polyethylene core 4 inches in diameter with the central cavity for the detector of thermal neutrons. Around this core, there is a 0.5-inch-thick spherical shell of tungsten and then 1-inch-thick polyethylene shell.
- 7Pb – same construction as 7W above, lead is used instead of tungsten.
- 9Pb – a sphere with the external diameter of 9 inches, consisting of a polyethylene core 5 inches in diameter with the central cavity for the detector of thermal neutrons. Around this core, there is a 1-inch-thick spherical shell of lead and then 1-inch-thick polyethylene shell.

During the preparatory experiments, it became apparent that the detector of thermal neutrons, spherical proportional counter SP9 (sensitive volume of ⌀ 32 mm) filled with ^{3}He under nominal pressure of 200 kPa (supplied by CENTRONIC, UK) was too sensitive for the measurements at the PTC. Therefore, it was replaced by a smaller one, LMT-0.5NH1/1KF (produced by LCC Thomson CSF, France). This detector is cylindrical with sensitive volume ⌀ 9 mm × 10 mm filled with ^{3}He under nominal pressure of 800 kPa.