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NEUTRON *H**(10) INSIDE A PROTON THERAPY FACILITY: COMPARISON BETWEEN MONTE CARLO SIMULATIONS AND WENDI-2 MEASUREMENTS

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Inside an IBA proton therapy centre, secondary neutrons are produced due to nuclear interactions of the proton beam with matter mainly inside the cyclotron, the beam line, the treatment nozzle and the patient. Accurate measurements of the neutron ambient dose equivalent *H(10) in such a facility require the use of a detector that has a good sensitivity for neutrons ranging from thermal energies up to 230 MeV, such as for instance the WENDI-2 detector. WENDI-2 measurements have been performed at the Westdeutsches Protonentherapiezentrum Essen, at several positions around the cyclotron room and around a gantry treatment room operated in two different beam delivery modes: Pencil Beam Scanning and Double Scattering. These measurements are compared with Monte Carlo simulation results for the neutron *H**(10) obtained with MCNPX 2.5.0 and GEANT4 9.6.**

In proton therapy, proton beams with energies up to typically 230 MeV are used to treat cancerous tumours very efficiently while sparing surrounding healthy tissues as much as possible. Due to nuclear interactions of the proton beams with matter, mainly inside the cyclotron, the beam line, the treatment nozzle and the patient, secondary neutrons with energies up to 230 MeV are unfortunately produced, as well as photons up to ~10 MeV [1, 2]. Behind the thick concrete shielding walls which are necessary to attenuate the stray radiation fields, the total ambient dose equivalent *H**(10) is very large due to the neutron component[3, 4].

In shielding studies for proton therapy facilities, the neutron *H**(10) component is often evaluated using the Monte Carlo codes MCNPX[5], FLUKA[6] or PHITS[7]. Recent benchmark simulations performed with GEANT4[8, 9] have shown that this code would also be a suitable tool for the shielding studies of proton therapy centres[10].

The experimental validation of such shielding studies requires the use of a detector with a good sensitivity for neutrons ranging from thermal energies up to 230 MeV, such as for example the extended-range neutron rem meter WENDI-2, developed in the 1990s by Olsher[11] and nowadays commercialised by Thermo Scientific. Although the response function of the WENDI-2 detector is not ideal, it is rather well balanced with respect to the fluence-to-*H**(10) conversion function from ICRP Publication 74[12].

This paper presents the measurements performed with a WENDI-2 detector at the Westdeutsches Protonentherapiezentrum Essen (Germany) at several positions around the cyclotron room and a gantry treatment room operated in two beam delivery modes, respectively, called Pencil Beam Scanning (PBS) and Double Scattering (DS). These measurements are compared with Monte Carlo simulation results for the neutron *H**(10) rate obtained with both the codes MCNPX 2.5.0 and GEANT4 9.6.

METHODS AND PROCEDURES

Experimental set-up in the cyclotron room

Around the cyclotron room, WENDI-2 dose rate measurements lasting 1 min were performed at the positions labelled from *a* to *g* in Figure 1a. The WENDI-2 detector was placed at ~1 m above the ground, except in position *g* where the device stood on the ground behind the vault door. The proton beam of 230 MeV extracted from the cyclotron had an intensity of 300 nA with a duty cycle of 50 % and was fully stopped inside the nickel beam stop located on the degrader wheel of the energy selection system (ESS).

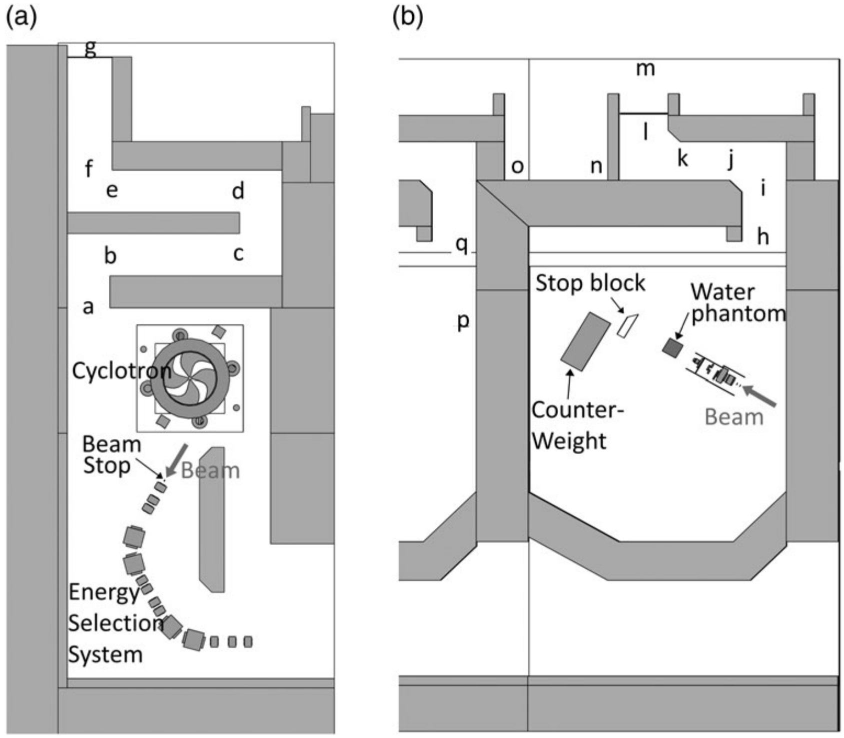

Figure 1. Simulated geometry of (**a**) the cyclotron room and (**b**) the gantry room.

Experimental set-up of the PBS irradiation

The positions (labelled from *h* to *q*) at which WENDI-2 measurements were performed around the gantry treatment room are shown in Figure 1b. The WENDI-2 detector was placed at ~25 cm above the floor in positions *h* to *m*, and at ~1 m height in positions *n* to *q*. The beam was shot horizontally in the direction of the accessible area of the adjacent treatment room, which is considered as the worst shooting angle from the radiation protection point of view. A simple PBS irradiation was considered in which a single fixed narrow proton beam of 226.7 MeV was directed towards the gantry isocentre. A phantom filled with $64\times64\times45$ cm^3 of water was positioned in such a way that the isocentre lied in its vertical entrance plane, at 15 cm under the water surface. The corresponding proton range in water is 32.2 cm. A constant beam intensity of 2 nA (at the nozzle entrance) was used, corresponding to an average proton dose rate in 1 l of ~10 Gy min^{-1}. The exact proton charge delivered to the phantom during each WENDI-2 measurement was monitored using a Bragg Peak Chamber Type 34070 placed at the isocentre. For every position located outside the vault, a few hundred counts could be recorded with the WENDI-2 in <10 min of irradiation.

Experimental set-up of the DS irradiation

WENDI-2 measurements were performed at the same positions as in the PBS case, except that in positions *p* and *q* the detector was placed on the ground. The gantry was positioned at the same angle as in the PBS case. Double Scattering is a passive irradiation technique in which the proton beam is enlarged by scattering through several nozzle elements in order to produce a field wide enough to cover the lateral extent of the tumour. In this case, a simple DS configuration was selected in which a proton beam of 227.5 MeV (at the nozzle entrance) is enlarged to a 16-cm diameter field at the isocentre. This isocentre was located in the entrance plane of a $64\times64\times40$ cm^3 water phantom, at 16 cm below the water surface. With the selected DS configuration, the proton range in the water phantom is 28.2 cm. The WENDI-2 measurements were performed using a constant beam intensity of ~18 nA at the nozzle entrance, corresponding to an average proton dose rate in 1 l of ~10 Gy min^{-1}. In these conditions, a few hundred counts could be recorded with the WENDI-2 detector within only a couple of minutes at the positions with the lowest dose rates. During each WENDI-2 measurement, the delivered monitor units from the IC23 ionisation chamber located inside the treatment nozzle were recorded. The relationship between these monitor units and the number of protons delivered at the nozzle entrance was established through a preliminary series of current measurements using a Bragg Peak Chamber Type 34070 at the isocentre, with the nozzle set in pass-through mode.

Monte Carlo simulations

To compute the neutron $H^*(10)$, the neutron spectra at the various considered measurement positions have been simulated using energy bins centred on the energies at which the fluence-to-$H^*(10)$ conversion function is defined within the ICRP Publication 74[(12)] (up to 201 MeV) and the work of Sannikov and Savitskaya[(13)] (>201 MeV).

For all MCNPX and GEANT4 simulations, it has been necessary to rely on a variance reduction technique based on geometry splitting and Russian roulette.

In the MCNPX simulations, the available la150 proton and neutron interaction cross-section tables have been used. Above 150 MeV, the nucleon–nucleus interactions have been calculated with the default Bertini model for the intranuclear cascade and the default Dresner ATC80 model for the evaporation. The GEANT4 simulations have used the 'Shielding' physics list, which includes cross-section data defined up to 20 MeV and the default Bertini-like intranuclear cascade and Weisskopf evaporation models.

For the cyclotron room study, four secondary neutron sources have been considered: the beam stop, the septum in the extraction channel of the cyclotron and the two pairs of cyclotron counter-Ds. To model the neutron sources located inside the cyclotron, which are difficult to quantify in practice, a simplified conservative approach has been adopted in which the proton beam losses are concentrated in three points located on the circumference of the accelerator cavity. The double-differential distribution of the corresponding neutron production in these points has first been calculated separately considering a 230-MeV proton beam impinging on a thick cylindrical copper target (diameter=length=7 cm). Based on values provided by Ion Beam Applications (IBA), it has been assumed that 60 % of the accelerated protons are lost inside the cyclotron (40 % on the septum and 10 % on the two groups of counter-Ds) and that the remaining 40 % hit the nickel beam stop of the degrader wheel. The whole ESS is nevertheless represented in the simulated geometry.

The PBS irradiation has simply been modelled by defining in front of the water phantom a Gaussian proton source with a standard deviation of 3 mm. For the DS case, the same proton source has been defined just at the entrance of the treatment nozzle, from which all beam shaping elements have been modelled.

RESULTS AND DISCUSSION

The WENDI-2 measurements carried out around the cyclotron room, the gantry room operated in PBS and the gantry room operated in DS are compared with the $H^*(10)$ values obtained with MCNPX and GEANT4 in Figures 2–4, respectively. For the gantry room (PBS and DS), the results have been normalised to an average proton dose rate in 1 l of 2 Gy min^{-1}. This average is calculated in the water phantom over a volume of $10\times10\times10$ cm^3 that is distally limited by the proton range. For the simulation results, only the statistical uncertainties (1σ) are reported in the figures. The reported global uncertainties (1σ) on the WENDI-2 measurements take into account the statistical counting uncertainty, the uncertainty on the angular dependence of the detector sensitivity ($\pm$ 20 %[(14)]) and the uncertainty on the delivered beam current (5 % for the PBS and DS cases and an upper estimate of 20 % for the

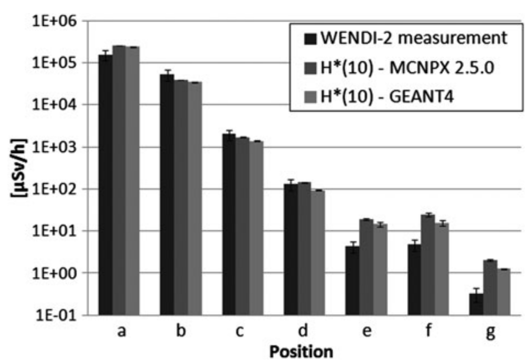

Figure 2. Measurements vs. simulated results of the neutron $H^*(10)$ rate around the cyclotron room.

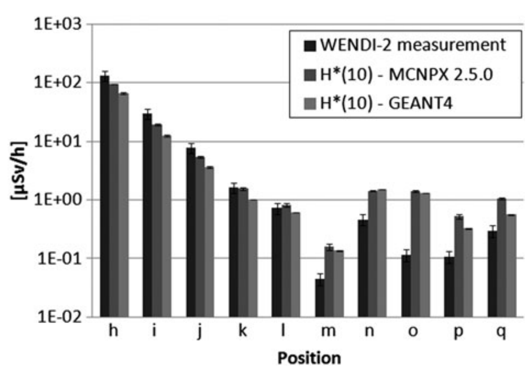

Figure 3. Measurements vs. simulated results of the neutron $H^*(10)$ rate around the gantry room operated in PBS.

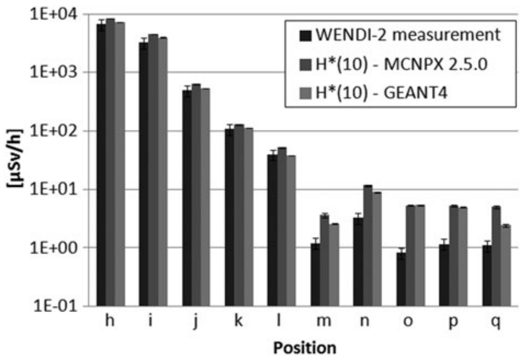

Figure 4. Measurements vs. simulated results of the neutron *H**(10) rate around the gantry room operated in DS.

cyclotron room in which the authors did not measure the beam current).

In the three case studies, a quite good agreement has been obtained between the MCNPX and GEANT4 results of the neutron *H**(10). In the cyclotron room study, all MCNPX results are larger than the GEANT4 results, by 9 % in position *a* to 63 % in position *g*. Around the gantry room operated in PBS, the MCNPX values are higher than the GEANT4 values by 9–91 %, except for position *n* where the GEANT4 result is 7 % larger than the MCNPX result. In the DS case, the MCNPX results are also larger than the GEANT4 values by 7–209 %, except for position *o* in which both codes give nearly identical results.

Generally speaking, the simulated *H**(10) values are in relatively good agreement with the measured WENDI-2 responses (within a factor of 2.5) inside the mazes of the studied rooms, or at least, inside some portion of these mazes. For the first four positions inside the maze of the cyclotron room (positions *a* to *d*), the *H**(10)/WENDI-2 measurement ratios lie between 0.7 ± 0.2 and 1.7 ± 0.5. In the maze of the PBS study (positions h to *l*), these ratios lie between 0.4 ± 0.1 and 1.1 ± 0.3. The best match between the simulated *H**(10) results and the WENDI-2 measurements has been obtained in the maze of the DS case, with ratios between 1.0 ± 0.2 and 1.4 ± 0.3 (positions *h* to *l*). However, this does not necessarily imply that the simulated neutron spectra are more realistic in the DS case. That seems indeed quite unlikely given the greater complexity of the DS simulation compared with the PBS case. The point might be that the WENDI-2 detector has been calibrated for a ^{252}Cf spectrum, which is undoubtedly quite different from the neutron spectra that one is dealing with inside the proton therapy centre. Therefore, future work will be dedicated to the determination of specific calibration correction factors that should be applied to these WENDI-2 measurements.

At all positions located outside the vaults, the simulated *H**(10) values systematically overestimate the WENDI-2 measurements. In position *g*, behind the vault door of the cyclotron room, a ratio of 6.3 ± 2.3 with MCNPX and 3.9 ± 1.5 with GEANT4 has been found between *H**(10) and the measured value. Outside the gantry room operated in PBS, this ratio varies between 1.9 ± 0.4 (GEANT4, position *q*) and 4.9 ± 1.2 (MCNPX, position *p*), except in position *o* where a much larger ratio has been obtained (12 ± 3 with MCNPX). The results of this study in position *q* are comparable to those of a similar study performed by Satoh *et al.*[15] at the Fukui proton therapy centre. The cause behind the larger discrepancy in position *o* is suspected to be related to the steel mechanical structure of the gantry that was not represented in the simulation. As for the positions located outside the gantry room operated in DS, the overestimation factor varies between 2.1 ± 0.4 (GEANT4, position *m*) and 6.6 ± 1.4 (GEANT4, position *o*).

Despite the fact that no calibration correction factors have yet been applied to the WENDI-2 measurements, the results of the three case studies give a strong indication that the Monte Carlo shielding simulations must be conservative. It appears that the simulated neutron spectra are probably less realistic at the external positions than inside the maze. However, the larger observed discrepancies for external positions might also partly be due to the larger proportion of high-energy neutrons in these spectra, because the errors in the high-energy part of the spectra are multiplied by higher values of the fluence-to-*H**(10) conversion function. In future work, the systematic uncertainties associated with the simulation results will be investigated through sensitivity analyses concerning geometrical aspects, material definitions and physics models.

CONCLUSION

In the three considered case studies, an overall good agreement (within a factor of 2) has been obtained between neutron *H**(10) values calculated with MCNPX 2.5.0 and GEANT4 9.6. The MCNPX code has yielded the largest values in nearly all cases.

For most positions located inside the access mazes of the rooms, the simulated results match the measured WENDI-2 responses within a factor of 2.5. Outside the shielded rooms, all simulation results overestimate the WENDI-2 measurements by approximately factors of 2–7, except for position *o* in the PBS study (factor of 12 with MCNPX). Future work will focus on the various systematic uncertainties associated with the simulation results and on the determination of calibration correction factors for the WENDI-2 measurements. However, the present results already give a strong impression that the assumed conservative nature of these Monte Carlo shielding simulations might be confirmed.

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