MCNPX SIMULATIONS OF THE RESPONSE OF THE EXTENDED-RANGE REM METER WENDI-2

by

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Proton therapy uses proton beams with energies typically between 50 and 230 MeV to treat cancerous tumors very efficiently, while protecting as much as possible surrounding healthy tissues from radiation damage. Protons interacting with matter inevitably induce secondary radiation from which all people inside the proton therapy center have to be protected. The ambient dose equivalent $H^*(10)$ in such a facility is mainly due to neutrons, which can have energies up to 230 MeV. Although various dose monitoring systems sensitive to high energy neutrons have already been developed, the response function of these detectors is often insufficiently characterized, and so are the calibration factors appropriate for the specific neutron spectra encountered inside a proton therapy facility. In this work, the Monte Carlo code MCNPX 2.5.0 has been used to study the response function of the extended-range rem-meter WENDI-2 from thermal energies up to 5 GeV. A good match has been obtained with equivalent simulation results found in literature. As a first step towards the characterization of the WENDI-2 response in continuous neutron fields, MCNPX simulations have also been carried out for the case-study of a bunker around an 18 MeV H^- cyclotron, which involves neutron fields from thermal energies up to 18 MeV.

Key words: neutron dosimetry, MCNPX simulation, response function, rem-meter, WENDI-2

INTRODUCTION

Context

As heavy charged particles, protons deposit the largest part of their energy near the end of their trajectory through matter. This feature allows proton therapy to treat cancerous tumors very efficiently, while protecting as much as possible surrounding healthy tissues from radiation damage. Inside a proton therapy center, an important radiation protection issue that has to be dealt with is the area monitoring of neutron doses. Secondary neutrons are produced by interactions of protons with matter, mainly in the accelerator, the beam line, the treatment nozzle and the patient. Since the used proton beams have energies typically between 50 and 230 MeV, the secondary neutrons can have up to 230 MeV. Dosimetry of continuous neutron fields with high energy neutrons ($E > 20$ MeV) is not trivial. First of all, the response functions of existing neutron detectors sensitive to high energy neutrons are often poorly characterized. Indeed, they can be simulated with Monte Carlo codes but they need to be validated by experimental data, which at high energies is more complicated to obtain since the only existing accurately characterized high energy neutron sources are quasi-monoenergetic neutron beams which are of limited availability throughout the world. Secondly, the calibration of the neutron detectors depends on the considered neutron spectrum, which requires introducing correction factors for measurements performed in neutron fields that differ from the calibration field.

The ambient dose equivalent $H^*(10)$

The operational quantity used in radiation protection for area monitoring of penetrating radiation is the ambient dose equivalent $H^*(10)$, which is used as an estimator of the effective dose E. The ambient dose equivalent $H^*(10)$ at a point is the dose equivalent that would be produced by the corresponding expanded and aligned field at a depth of 10 mm in the ICRU sphere, on the vector radius opposing the direction of radiation incidence [1].

Through a Monte Carlo simulation, the neutron $H^*(10)$ at a given point can be estimated as

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$$H^{*}(10) \quad h_{\phi}(E)\phi(E)\mathrm{d}E \tag{1}$$

where $\phi(E)$ is the neutron fluence energy function and $h_{\phi}(E)$ the neutron fluence-to-$H^{*}(10)$ conversion function established up to 201 MeV by the ICRP Report 74 [1] and extended up to 5 GeV by Sannikov and Savitskaya [2].

Rem-meters and the WENDI-2 detector

Rem-meters are since long widely in use for the area monitoring of neutron doses. The response of a rem-meter is given by

$$R \quad C \ r(E)\phi(E)\mathrm{d}E \tag{2}$$

where $\phi(E)$ is the neutron fluence energy function, $r(E)$ – the absolute response function (expressed in counts per unit fluence), and C – the calibration factor (expressed in Sievert per count). Rem-meters consist of a thermal neutron detector surrounded by a moderator assembly designed so that the dose response function $Cr(E)$ approximately follows the aforementioned h_{ϕ}(E) conversion function over a wide energy range.

Traditional rem-meters, such as the Andersson-Braun and the Hankins rem-meters [3, 4], consist typically of a polyethylene-based assembly surrounding a proportional BF_3 or ^{3}He counter and have a sensitivity that tends to decrease strongly for neutrons above 10 MeV. In the 1990's, Birattari *et al*. introduced the idea to insert a heavy metal layer such as lead in the moderator assembly, in order to enhance the response above 8 MeV thanks to spallation reactions (n, xn) [5]. The WENDI detector (Wide Energy Neutron Detection Instrument), developed from 1992 onwards by Olsher *et al*. [6], at the Los Alamos National Laboratory, is based on the same idea, but tungsten is used instead of lead. Tungsten has a high absorption resonance structure between 0.1 and 1.5 keV, which helps to reduce the $H^{*}(10)$-overestimating response at intermediate energies [6]. A cutaway view of Olsher's latest design, the WENDI-2 detector manufactured by Thermo Fisher Scientific, is given in fig. 1.

Contents

A preliminary study of the WENDI-2 detector response has been carried out with the Monte Carlo code MCNPX 2.5.0 [7]. First, the WENDI-2 absolute response function has been simulated from thermal energies up to 5 GeV. Secondly, the dose response function of the detector has been established and compared to the fluence-to-$H^{*}(10)$ conversion function. The normalization of this dose response function is based on factors obtained from ^{252}Cf calibration data. Thirdly, the same normalization has been applied in the simulation of the WENDI-2 response inside a workplace, named "IBA Academy", which involves continuous neutron fields ranging from thermal energies up to 18 MeV.

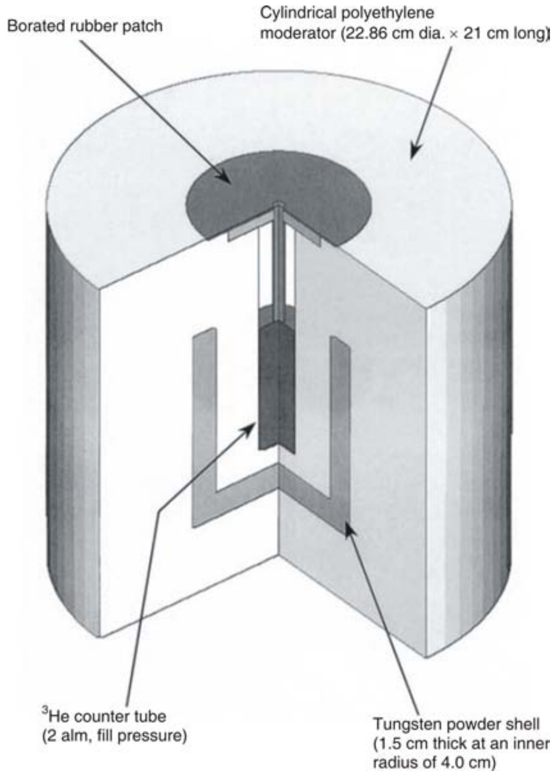

Figure 1. Cutaway view of the WENDI-2 detector [6]

METHODS AND PROCEDURES

Simulation of the WENDI-2 response function

The WENDI-2 absolute response function, expressed in counts per unit fluence, has been evaluated with MCNPX 2.5.0 for 93 neutron energies between 10^{-3} eV and 5 GeV, considering a side irradiation from a monoenergetic point source located at 50 cm from the centre of the detector. As a variance reduction method, the isotropic emission of neutrons has been reduced to the solid angle delimited by a cone circumscribed to the WENDI-2 detector. The value of the absolute response function at a given energy has been calculated as the ratio of two simulation results: the detector is modeled in the first simulation in order to estimate the average number of counts per source-emitted neutron, while the second simulation only considers air and evaluates the average neutron fluence per source-emitted neutron inside a cylindrical volume, corresponding to the counter tube's active volume defined in the first simulation. Figure 2 shows the considered geometry in, respectively, the first (a) and the second (b) simulation.

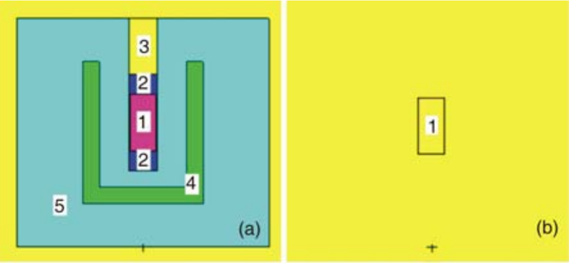

Figure 2. Simulated geometry of (a) the WENDI-2 detector and (b) the air volume for the average neutron fluence calculation

The modeled detector has a diameter of 22.86 cm and is 21 cm high [6]. Polyethylene has been defined with a density of 0.94 g/cm³ [8] and with an $S(\alpha,\beta)$ thermal treatment of hydrogen (cross-section table poly.01t, based on ENDF/B-V) [7] instead of the default free-gas thermal treatment. The tungsten powder shell has an effective density of 10.624 g/cm³ [8] and is 1.5 cm thick with an inner radius of 4.0 cm [6]. The borated rubber patch on top of the counter tube has been omitted. The modeled counter tube is a Cylindrical High Temperature He-3 Neutron Detector (type 252180) manufactured by LND [8]. The active volume of the tube is 23.95 cm³ and the ^{3}He mass density has been set to 2.4 10^{-4} g/cm³, corresponding to a gas pressure of 2 atm [8]. A generic composition of stainless steel has been considered for the tube itself (mass percentages: 74% Fe, 18% Cr, 8% Ni; density: 8 g/cm³).

In this preliminary work, only the main count generating mechanism, namely the ^{3}He(n, p)t reactions, has been taken into account to estimate the average number of counts per source-emitted neutron. According to Olsher, other contributions such as ^{3}He(n, d)d reactions and external charged particles travelling through the counter gas are very small and it can be considered safe to ignore them given the rather large uncertainties on the used physics models [6]. The average number of (n, p) reactions is obtained by folding the average neutron fluence in the ^{3}He volume with the ^{3}He(n, p)t cross-section, multiplied hereafter by the atomic density of the gas and the volume of the gas cell. At this stage, one (n, p) reaction has been considered to generate one count. The wall effect, which causes count losses due to low amplitude pulses (below the lower discriminator of the detector electronics), has thus not been taken into account in the simulation of the absolute response function. Neutrons, protons, photons and muons have been tracked in the simulations. Photonuclear reactions have been enabled and the la150 cross-section libraries [7] have been used wherever possible for neutrons, protons and muons. Where experimental cross-section data was not available, the default physics models implemented in MCNPX 2.5.0 have been used (for neutrons: BERTINI and DRESNER ATC80) [7]. In each simulation, 10^7 source-emitted neutron histories have been calculated and the MCNPX relative uncertainties are lower than 1%.

In order to obtain a dose response function (expressed in pSvcm²) that can be compared to the fluence-to-H^*(10) conversion function [1, 2], it is necessary to multiply the absolute response function by a calibration factor that takes into account the wall effect and the sensitivity (in counts per Sievert) of the detector. Here, the chosen calibration factor equals to 245.7 pSv/c and is the product of the wall-effect correction factor 0.743 experimentally determined with a bare ^{252}Cf source by Olsher for a previous WENDI-2 design including a GL-2500802-NS counter tube [6], and the factor 330.7 pSv/c that corresponds to the sensitivity of 0.84 (c/s)/(μSv/h) announced by Thermo Fisher Scientific for the currently commercialized WENDI-2 detector, also calibrated with a ^{252}Cf source [9]. Despite the fact that the wall-effect correction factor was obtained with a prototype detector, the chosen value of the calibration factor is expected to be close to what the experimentally determined value of the global ^{252}Cf calibration factor would be for a currently commercialized WENDI-2 detector.

WENDI-2 response inside the IBA Academy bunker

IBA Academy

Inside the assembly hall of the Company Ion Beam Applications S. A. (IBA), located in Louvain-la-Neuve, a bunker called "IBA Academy" is dedicated to the training of IBA clients. It contains a cyclotron ©Cyclone 18/9 that can accelerate H^- ions up to 18 MeV or $^2H^-$ ions up to 9 MeV. This type of cyclotron is normally used for the production of a wide range of PET-radiotracers. When 18 MeV H^- ions hit a radio-isotope production target, secondary neutrons are generated, leading to the presence of continuous neutron fields ranging from thermal energies up to 18 MeV.

Simulation of $H^*(10)$ per unit time

The neutron ambient dose equivalent H^*(10) per unit time has been calculated with MCNPX 2.5.0 for nine positions inside the IBA Academy bunker, considering a 20 μA beam of 18 MeV H^- ions impinging on a water target with a 100% ^{18}O-enrichment. The considered positions, from which three are located inside the cyclotron room and six inside the maze, are indicated in fig. 3.

The angular distribution of secondary neutrons and the corresponding energy spectra have been studied separately, by simulating the irradiation of a thick 100% ^{18}O-enriched water target by an 18 MeV proton

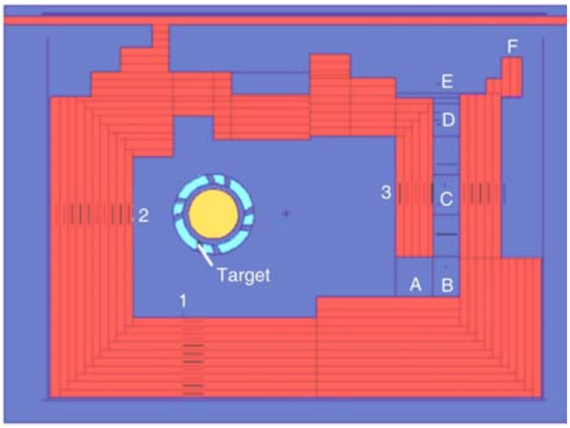

Figure 3. Simulated geometry of the IBA Academy bunker

beam directed along the axis of the cylinder. The angular distribution is based on twenty bins delimited by integer cosine values of the angle formed with the direction of the proton beam. The total neutron yield (results integrated over all angular and energy bins) equals 6.95 10^{-3} per proton. The obtained angular and energy distributions have then been introduced in the definition of the neutron source of the IBA Academy simulation.

Around each considered position, a parallelepipedic air cell (50 cm 50 cm 1 cm) has been defined, over which the average neutron fluence spectrum has been folded with the fluence-to-$H^*(10)$ conversion function [1, 2]. Based on the aforementioned total neutron yield and H^- beam current, the results in Sievert per neutron have been multiplied by 3.12 10^{21} in order to express them in units of µSv/h.

Simulation of the WENDI-2 response

MCNPX 2.5.0 has also been used to compute the response of the WENDI-2 detector in the nine positions indicated in fig. 3, using the same neutron source definition as in the previously mentioned calculation of $H^*(10)$ per unit time. Nine separate simulations have been run, with the WENDI-2 detector inserted at one given position in the IBA Academy geometry. The responses in µSv/h have been estimated by multiplying the average number of (n, p) reactions per source-emitted neutron by 7.68 10^{11}, assuming a current of 20 µA, a neutron yield of 6.95 10^{-3} per proton, a wall-effect correction factor of 0.743 [6] and a sensitivity of 0.84 (c/s)/(µSv/h) [9].

RESULTS AND DISCUSSION

WENDI-2 absolute response function

The absolute response function of the WENDI-2 detector computed with MCNPX 2.5.0 is compared in

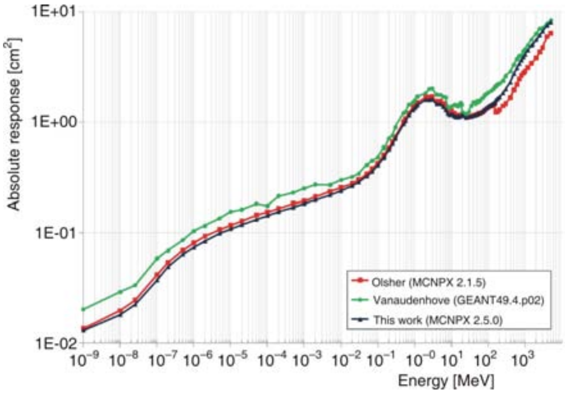

Figure 4. Simulation results of the WENDI-2 absolute response function [6, 8]

fig. 4 to Vanaudenhove's work [8] using GEANT4 9.4.p02 (with similar simulation conditions) and to Olsher's curve [6] obtained with MCNP4B up to 20 MeV, and with MCNPX 2.1.5 between 20 MeV and 150 MeV, but considering a different ^{3}He counter tube (the GL-2500802-NS from Gamma Labs). There is quite a good agreement between the three curves. Below 30 MeV, our values are lower than Olsher's by at most 10%. Between 30 MeV and 150 MeV, they exceed Olsher's by less than 4%. Above 150 MeV, our values are greater than Olsher's by maximum 46%. The larger discrepancies in this high energy region might be explained by the difference in the intranuclear cascade model used (BERTINI in our case *vs*. CEM in Olsher's work). Compared to Vanaudenhove's curve, our results are lower over the whole considered energy range, by 5 to 38%. In future work, systematic uncertainties associated to our absolute response function simulation will be investigated through sensitivity analyses concerning *e. g.*, physics models, geometrical aspects, material definitions, minor count generating mechanisms and the wall effect.

WENDI-2 dose response function

The obtained dose response function is shown in fig. 5 and the corresponding relative dose response function, *i. e.*, the ratio of the dose response function and the fluence-to-$H^*(10)$ conversion function, is given in fig. 6. Between 10^{-3} eV and ~0,3 eV (thermal energies) and between ~150 keV and ~80 MeV (fast and high energy neutrons), the dose response function underestimates the fluence-to-$H^*(10)$ conversion function by a factor less than 2.1. For neutrons between ~80 MeV and 5 GeV, the dose response function overestimates the fluence-to-$H^*(10)$ conversion function by a factor between 1.2 and 2.1. The most critical energy range seems to be the intermediate energies, where the overestimation factor grows up to 6.7 at 5 keV.

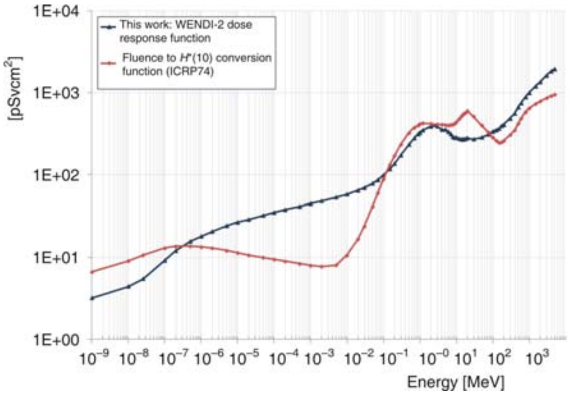

Figure 5. Simulation results of the WENDI-2 dose response function compared with the fluence-to-*H**(10) conversion function [1, 2]

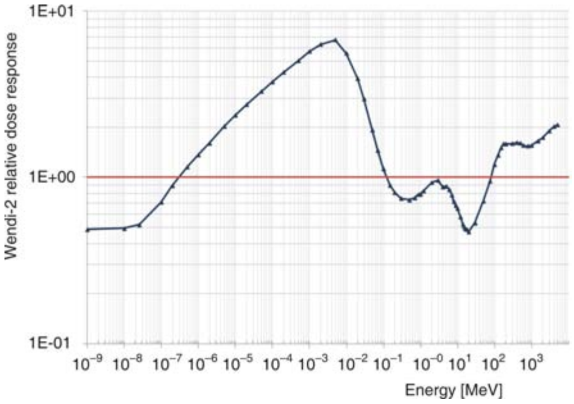

Figure 6. Simulation results of the WENDI-2 relative dose response

WENDI-2 response in IBA Academy

For the nine considered positions inside the IBA Academy bunker, the neutron ambient dose equivalent $H^*(10)$ per unit time, the WENDI-2 dose response and the WENDI-2 relative response (ratio of the dose response and $H^*(10)$ per unit time) are given in tab. 1. The WENDI-2 dose response underestimates $H^*(10)$ by almost a factor 1.3 in position 1 located in front of the target. In other positions, the response overestimates $H^*(10)$ by a factor up to 2.2. It appears that the considered calibration factor is the most appropriate for the neutron spectrum found in position 2 inside the cyclotron room, and the least compatible with the neutron field in position *F* at the exit of the maze.

CONCLUSIONS

A preliminary study of the response of the extended-range rem-meter WENDI-2, manufactured by Thermo Fisher Scientific, has been performed with MCNPX 2.5.0. The absolute response function of the detector has been calculated from thermal energies up to 5 GeV and results similar to those existing in literature [6, 8] have been obtained. The corresponding dose response function (obtained using ^{252}Cf calibration data [6, 9]) has been compared to the ICRP fluence-to-$H^*(10)$ conversion function [1, 2], showing two underestimation and two overestimation energy regions. The response at intermediate energies appears to be the detector's weakest point, with an overestimation factor going up to 6.7 at 5 keV. Future work will be dedicated to the study of the systematic uncertainties associated to our simulation results.

In a first attempt to characterize the behavior of the WENDI-2 detector in continuous neutron fields, the specific case of the IBA Academy workplace has been considered. The simulated dose response has been compared to the neutron $H^*(10)$ per unit time in nine positions, in which the neutron spectrum ranges from thermal energies up to maximum 18 MeV. In all positions but one, the WENDI-2 response overestimates $H^*(10)$ under the influence of the intermediate neutrons in the energy spectrum. The overestimation reaches up to a factor 2.2 for the most distant position with respect to the neutron source.

Table 1. Simulation results of the IBA Academy case-study

Position	H*(10) per unit time [μSvh^{-1}]	MCNPX relative uncertainty on $H^*(10)$ per unit time	WENDI-2 response [μSvh^{-1}]	MCNPX relative uncertainty on WENDI-2 response	Relative WENDI-2 response	Absolute uncertainty on relative ENDI-2 response
1	1.30E+07	0.0011	1.03E+07	0.0082	0.79	0.01
2	1.99E+06	0.0032	2.08E+06	0.0151	1.05	0.02
3	3.62E+05	0.0059	4.50E+05	0.0316	1.24	0.04
A	2.04E+05	0.0065	2.68E+05	0.0416	1.31	0.06
B	1.47E+05	0.0077	1.92E+05	0.0475	1.31	0.06
C	9.89E+03	0.0158	1.40E+04	0.0628	1.42	0.09
D	1.94E+03	0.0279	4.13E+03	0.0760	2.13	0.17
E	9.39E+02	0.0426	1.89E+03	0.0567	2.02	0.14
F	4.62E+01	0.0411	1.00E+02	0.0478	2.17	0.14

AUTHOR CONTRIBUTIONS

The simulation work was carried out by V. De Smet and S. Tolo. The manuscript was written and the figures were prepared by V. De Smet. Both authors reviewed the manuscript.

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MCNPX СИМУЛАЦИЈА ОДЗИВА WENDI-2 REM ДЕТЕКТОРА ПРОШИРЕНОГ ОПСЕГА

У терапији протонима користе се протонски снопови енергија од 50 MeV до 230 MeV за веома успешно лечење канцерогених тумора и најбољу могућу заштиту околног здравог ткива. у интеракцији са материјалом протони неизбежно стварају секундарно зрачење од кога мора бити заштићено сво особље у центру за терапију. Јачина амбијенталног дозног еквивалента $H^*(10)$ у оваквим установама потиче углавном од неутрона који могу имати енергије и до 230 MeV. Мада постоје разни системи мониторинга дозе осетљиви на неутроне високих енергија, функција одзива ових детектора често је недовољно описана, а тиме и калибрациони фактори одговарајући за специфичне спектре неутрона који се срећу унутар установа за терапију протонима.

У овом раду коришћен је Монте Карло програмски код MCNPX 2.5.0 за проучавање функције одзива WENDI-2 REM дозиметра проширеног опсега у распону енергија од термичких до 5 GeV. Уочено је добро поклапање добијених резултата са подацима пронађеним у литератури. Као први корак ка карактеризацији одговора WENDI-2 дозиметра у сталном неутронском пољу, обављене су MCNPX симулације и за случај бункера око H^- циклотрона енергије 18 MeV, које укључују и неутронско поље од термичких енергија до енергија од 18 MeV.

Кључне речи: неутронска дозиметрија, MCNPX симулација, функција одзива, REM дозиметар, WENDI-2