Assessment of individual neutron dosemeters in the design of the operational radiation protection of Compact Proton Therapy Centers (CPTC) using MCNP6.2 and GEANT4 Monte Carlo codes

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Abstract

Proton therapy, an external radiotherapy using proton beams with energies between 50 and 230 MeV, is in continuous ever evolving and improvement to obtain more precise and beneficial treatments for patients. Some prominent current trends involve cutting-edge delivery techniques or building compact proton therapy centers (CPTC), merging the most advanced technologies, reducing their size while achieving more affordable facilities. In the interaction of protons of therapy, a huge production of stray radiation is yielded, mainly neutrons, therefore optimal selection of individual neutron dosemeters for exposed workers is a key task in the operational radiation protection of CPTC. Individual neutron dosimetry continues to be one of the problems in radiation protection, as no single method provides the combination of energy response, sensitivity, orientation dependence characteristics and accuracy necessary to meet the requirements of a personnel dosimeter. Furthermore, neutron dosemeters should be subject to measurement uncertainties in compliance with the recommendations given in European Commission Report Radiation Protection 160. The aim of this work was to characterize the performance of different personal neutron dosemeters, through the Monte Carlo codes, as MCNP6 and GEANT4. The work is framed into the project Contributions to operational radiation protection and neutron dosimetry in compact proton therapy centers (CPTC), which is focused on assessing the impact of innovations on the operational radiation protection and commissioning of these facilities.

Keywords: Compact proton therapy centers; individual neutron dosemeters; MCNP6.2; GEANT4
1. - INTRODUCTION

The advantages of proton therapy (PT) in treatments against cancer have led to a relevant expansion of proton therapy centers (PTC) around the world, and almost one hundred are currently working [PTCOG, 2021]. Proton therapy, with more than sixty years of life, is constantly evolving and improving to obtain more precise and beneficial treatments for patients. Some prominent current trends involve building small Compact Proton Therapy Centers (CPTC), standard centers incorporating the most advanced technologies, to reduce their size while achieving more affordable facilities, usually with one treatment room or sometimes two. Another important trend is the renovation of the multiple room centers (MPTC), built in the early stages of PT [Bortfeld and Loeffler, 2015].

In the interaction of protons with the elements of the line and the patient, neutrons of up to 230 MeV are yielded, consequently, in recent years there has been a great development of dose delivery methods, from the initial passive systems, made up of different metallic elements and openings, to adapt the shape of the proton beam to the treated volume, up to modern active systems, based on spot scanning or pencil beam scanning (PBS), where the protons are drive by fields magnetic towards the tumour area. Nowadays there are several innovative dose application techniques in the research phase, such as proton arc therapy (PMAT), proton-minibeams, or flash-therapy [Carabe-Fernández et al., 2019].

This work is framed into the research project Contributions to operational radiological protection and neutron dosimetry in CPTC, which is focused on assessing the impact of some of the innovations aforementioned on the operational radiation protection (RP) and RP commissioning of these facilities [García-Fernández et al., 2019a]. Thus, several tasks linked to such project have been carried out over the last three years in fields as checking shielding [García-Fernández et al., 2021], comparing ambient equivalent dose, H*(10), by neutrons, in several CPTC [García-Fernández et al., 2020a], analysing activation in shielding with different types of concrete [García-Fernández et al., 2020b], characterizing wide range Rem-meters to measure neutron fields [García-Fernández et al., 2019b], or intercomparing new proton delivery techniques as PMAT of flash-therapy with
conventional therapy (IMPT, intensity modulated proton therapy) and their associated neutron fields yielded [García-Fernández et al., 2020c], among others.

Individual neutron dosimetry continues to be one of the problems in radiation protection, as no single method provides the combination of energy response, sensitivity, orientation dependence characteristics and accuracy necessary to meet the requirements of a personnel dosemeter. Furthermore, neutron dosemeters should be subject to a permanent assessment and measurement of uncertainties in compliance with the recommendations given in European Commission Report Radiation Protection 160 [EC, 2009].

Thus, personal dosimetry in mixed fields is not yet properly resolved and it is usually necessary to use different types of dosemeters to achieve reliable gamma and neutron doses. While neutron dosimetry in the thermal and epithermal range is enough and is well developed, this is not the case in the fast and relativistic range. Hence, in complex cases it would be not only necessary different types of dosemeters for mixed fields of neutrons and photons, but even in wide-range neutron fields as proton centers, different types of dosimeters would be necessary as a function of the energy of the neutrons, since there is no single neutron dosimetry that covers the entire energy range [Mendez et al., 2002].

The main reasons because personal neutron dosimetry is so difficult could be summarized as follow [Vega-Carrillo et al., 2018]:

1. Neutrons are always yielded along with, usually, strong gamma fields.
2. The energy range of the neutron fields is very wide, with more than nine orders of magnitude, from thermal (0.025 eV) to hundreds of MeV.
3. To evaluate the biological damage due to neutrons, it is necessary to estimate the equivalent dose, which directly depends on a weighting factor as a function of the energy of the neutron. For example, fast neutrons are much more harmful than thermal neutron (per Linear Energy Transfer, LET or deposited energy).
4. Although detection of thermal neutrons is well developed, pristine neutrons are born as fast or even relativist neutrons, transferring dose before becoming thermal.
5. Personal dose depends strongly on neutron energy and angle.
Although there is a great diversity and typology of personal neutron dosemeters, these can be gathered into two main classes, active and passive. At the same time there are several types of neutron passive dosemeters as track etch, albedo and bubble. Active are usually known as electronic dosemeters, DLDs or EPDs [Spurny, 2005].

The operational quantity used for external irradiation is the personal dose equivalent, \( H_p(d) \), which provides a reasonable overestimation of the limiting quantities and can be measured with relatively simple instrumentation. \( H_p(d) \), is the soft tissue equivalent dose at an appropriate depth, \( d \), below a specified point in the human body. For strongly penetrating radiation, as neutrons, the assumed value of \( d \) is 10 mm. Personal equivalent dose strongly depends on both, neutron energy and angle as can be verified in the fluence to personal dose equivalent conversion function, \( h_p(E) \), \( \text{Sv} \cdot \text{cm}^2 \), used in calculating the personal dose. These coefficients depend on the five standard irradiation geometries selected by the ICRP and ICRU, antero-posterior (AP), postero-anterior, (PA), laterally, (LA), rotationally, (ROT), and isotropically (ISO) [ICRP, 1996].

Therefore, in facilities as proton centers, with mixed and complex fields of gamma and neutron radiation, it is essential to establish workplace field adjustments, known as local correction factors (LCFs) for personal dosimetry. Consequently, it is necessary to develop workplace monitoring and occupancy and a detailed knowledge of radiation fields as energy and angle distributions at different worker locations [Vanhavere, F. and Cauwels, V., 2014]. The dosimetric operational quantity usually used as reference to compare the performance and assessment of personal dosemeters is the ambient dose equivalent, \( H^*(10) \) [ICRP, 1996], experimentally measured or calculated with Monte Carlo codes.

The aim of this work was to characterize and to assess the performance of different personal neutron dosemeters, through the Monte Carlo codes, MCNP6 and GEANT4, for use in proton therapy centers. Three different types of personal dosimeters have been simulated, albedo passive dosemeter with TLD, passive dosemeter track etch and finally active electronic dosemeter. The personal dose equivalent, \( H_{p(10)} \) reached with personal dosemeters has been compared with ambient dose equivalent, \( H^*(10) \) ref, in two different
types of proton centers, one compact (CPTC) and one with multiple rooms (MPTC). $H^*(10)_{\text{ref}}$ used as dose of reference, has been calculated simulating three different types of neutron REM-meters, WENDI, LUPIN and Prescila, as the same places as the personal dosimeters. Finally, local corrections factors have been achieved, depending on the type of center and the type of dosimeter by dividing $H_p(10)_{\text{cal}}$ between $H^*(10)_{\text{ref}}$. Absolute response of neutron REM-meters used in the work had been characterized in previous works of the same research project, WENDI and LUPIN through MCNP6 code and PRECILA using GEANT4 Monte Carlo code.

2. - MATERIALS AND METHODS

2.1. – Dosemeters modelled and personal dose equivalent $H_p(10)_{\text{cal}}$,

Dosemeters characterized are several passive devices (albedo and track etch), included in the most recent EURADOS report [Mayer et al., 2020]. In the face of in many maintenance and supervision operations it is necessary to have real-time information of the dose to which the teams of professionals are exposed, for example in the accelerator zone, an active dosimeter was included in the assessment. Active dosemeters are known as DLDs, direct lecture dosemeters, or frequently as APDs, active personal dosemeters.

In 2017/2018, the second EURADOS intercomparison for neutron dosemeters (IC2017n) took place, and Figure 1 shows the responses, $R$, for all radiation fields, all systems, and all dosemeters (28 responses are plotted per system). They are ordered with Albedo on the left, and Track on the right. The dotted line at $R=2$ corresponds to the upper performance limit of ISO 14146:2018, and at $R=0.5$ serves as an eye guideline since the limit depends on the reference dose. This figure essentially allows all results to be compared and individual results for any system to be picked out [Mayer et al., 2020].
The main features of passive and active personal neutron dosemeters are collected as follows [Gilvin et al., 2016]:

a) Passive Dosemeters (albedo and track etch):
1. It is necessary to be collected and returned to individual monitoring systems (IMS) so it must be waiting a minimum of two weeks until the report.
2. It has no real-time capability.
3. Relatively cheap.
4. Suitable for mass monitoring.
5. Most are environmentally robust.
6. Discriminating: Different filters or elements required, can give information about the field and it is possible some types discriminate between static and mobile exposures.

b) Active personal dosemeters (APDs):
1. Real-time functions: Alarms, display, frequent updates to dose database (daily or more often).
2. High sensitivity.
3. High unit costs and maintenance costs.
4. Environmental limitations (low performance in pulsed fields with current devices).
5. Essential where high and/or variable dose rates are possible.
6. The device can fulfil legal role too.

Considering that neutron fields and exposition at workplaces in proton centers are very different that fields of calibration shown in 8925 and 12789 ISO standards, it would be necessary a methodology to ensure that the simulated workplace field is representative of the real workplace in which the dosemeter has to be characterized. Consequently, just the next three types of personal dosemeters have been assessed in this work.

2.1.1. **Passive dosemeter track etch type.** This personal dosemeters are based on chemical (or electro-chemical) amplification of the physical damage trails caused by secondary protons. They are passive dosemeters with special polymer (CR-39, PADC), where recoil protons create broken polymer chains. Tracks originated can be visualized under microscope by chemical etching. These devices have a relatively good energy response. The main elements of track etch dosemeter are collected in Figure 2.

![Figure 2.- Passive dosimeter track etch type simulated in the work](image)

2.1.2. **Passive dosemeter albedo type.** In this kind of dosemeters, detection of secondary radiations (gamma) arising from capture of thermal neutrons scattered back from body wearer the device. It is a passive dosimeter with two pairs of LiF thermoluminescent detectors, combination of $^6\text{LiF}$ and $^7\text{LiF}$ to distinguish neutrons and photons. One pair is
used to measure incoming thermal neutrons while the other is employed to measure backscattered fast and high energy neutrons. It is necessary a workplace specific empirical algorithm to combine the four detectors. The main elements of albedo dosemeter are collected in Figure 3.

![Figure 3.- Passive dosimeter albedo type simulated in the work](image)

2.1.3. Active dosemeter, DLD or APD type. The active electronic dosimeters (APDs) have three Si diodes, with hydrogen rich convertor for fast and high energy neutrons, with \(^6\)Li convertor for thermal neutrons and without convertor for photons. The dosemeter have multi-detector technology and direct display of Hp(10) for neutrons and photons, with immunity to electromagnetic interference and AA battery. The main elements of active dosemeter are collected in Figure 4.

![Figure 4.- Active dosimeter APD type simulated in the work](image)
2.1.4. Personal dose equivalent, \( H_p(10) \). The calculation of the dose is yielded by the convolution of the neutron fluence and the fluence to personal dose equivalent conversion coefficients [ICRP, 1996]. These coefficients, \( h_p(E) \), vary strongly with neutron energy as shown in Figure 5, because of the differences between the interactions that dominate for different energy regions: dose deposition by fast neutrons is mainly by elastic scattering whereas capture reactions dominate dose deposition for lower energies.

![Figure 5.- Fluence to personal dose equivalent conversion function, \( h_p(E) \), (Sv·cm\(^{-2}\))](image)

2.2. – Set-up of proton centers

2.2.1. Compact proton therapy centers (CPTC). The CPTC considered in this work has a cyclotron accelerator with extraction energy at 230 MeV and a footprint close to 360 m\(^2\). The general features of CPTC modelled are collected in Figure 6. Neutron measurement positions circled in Figure 6 are two at the accelerator west wall (W-a-I, inside the accelerator room, and W-a-O outside), two at the gantry south wall (S-g-I, inside the gantry room, and S-g-O outside), and one at the treatment control room (TCR). As an example, one of the spectra used in the work, corresponding to west wall (inside and outside), is shown in Figure 7.
Figure 6.- CPTC layout and measurement positions [García-Fernandez et al., 2021]

Figure 7.- Neutron spectra at several points of CPTC [García-Fernandez et al., 2021]
2.2.2. Multiple room proton therapy centers (MPTC). The MPTC considered in this work is the fixed beam room (FBTR) at the Roberts Proton Therapy Centers (RPTC) of the Penn University. The general features of MPTC modelled are collected in Figure 8.

Figure 8.- MPTC layout and measurement positions [Garcia-Fernandez et al., 2020c]

Neutron measurement positions circled in Figure 8 are two at the gantry (Positions 1 and 4), one at the technical room (TR1) and the last one at and at the treatment control and technical room (TCTR). As an example, one the spectra used in the work, corresponding to points inside gantry treatment room is shown in Figure 9.

Figure 9.- Neutron spectra at several points of MPTC [Garcia-Fernandez et al., 2020c]
2.2.3. Disposition of dosemeters in positions at proton centers. To achieving more precise calibration, based on the dispersion generated by the body, IAEA recommends practical conditions for the calibration of dosimeters, since these cannot be calibrated in front of a real human body. For this procedure, the human body should be replaced by a Phantom ISO, parallelepiped (30 cm x 30 cm x 15 cm), with PMMA walls filled with water (Figure 10). Front wall is 2.5 mm thick while the other five walls are 10 mm thick.

![Figure 10. - Disposition of dosemeters in simulations at the ISO phantom of PMMA](image)

2.2. – REM –meters and ambient dose equivalent, $H^*(10)_{\text{ref}}$

The personal dose equivalent, $H_{\text{p}(10)}_{\text{cal}}$ reached with personal dosemeters should be compared with ambient dose equivalent, $H^*(10)_{\text{ref}}$, at different positions of proton centers overmentioned, CPTC and MPTC, characterized in previous works.

$H^*(10)_{\text{ref}}$ used as dose of reference, has been calculated simulating three different types of neutron REM-meters, WENDI, LUPIN and PRESCILA, as the same places as the personal dosemeters. Absolute response of neutron REM-meters used in this work have also been characterized in previous works of the same research project. REM-meters WENDI and LUPIN were characterized through MCNP6 code [Garcia-Fernandez et al., 2019b], while the absolute response and characterization of PRESCILA scintillator was developed using...
GEANT4 Monte Carlo code [García-Fernández et al., 2020c]. On the one hand, the general features of REM-meters modelled in the project are collected in Figure 11.

Figure 11.- REM-meters to achieve \( H^*(10)_{\text{ref}} \) [García-Fernández et al., 2019b, 2020c]

On the other, absolute response of these neutron area monitors, compared with the fluence to ambient dose response function from ICRP74, are shown in Figure 12.
2.3. – MCNP6 settings and calculations

2.3.1. Physical model and MCNP models of dosemeters. To simplify the computation time, the geometry of the simulated dosemeters has been reduced to the maximum, and just the elements with impact on reactions with neutrons of different energies have been considered in the models.

As an example, Figure 13, adapted from [Barros and King, 2018], collects the physical model of several configurations corresponding to albedo dosemeter, and the corresponding simplification in MCNP with the active volume, that is, the elements reacting with neutrons, yielding a deposition of dose by these, and the cadmium filter.
Following previous work at the same project, dosemeter efficiency was assumed to be 100%, which means that each neutron triggers a count. Thus, other channels of reactions were neglected to the total count rate, due to the new model would be very complex while the improved accuracy is not very relevant [Garcia-Fernandez et al., 2019b].

2.3.2. **Channel reactions in dosemeters.** The average number of neutron reactions were computed by folding the average neutron fluence in the active volume of the dosemeter, with the corresponding cross section of interaction between neutrons and elements of the
active volume, multiplied by the atomic density of atoms in active volume reacting with neutrons (atoms/b-cm) and the active volume of each dosemeter (cm$^3$). The response function of the detector (counts·cm$^2$) was reached computing the total number of counts per unit fluence in the detection volume, with each value of neutron from spectra. This response function at a given energy was calculated as the ratio of two simulations: 1) Simulation with the complete dosemeter to compute the average number of counts generated in the active volume per source-emitted neutron; 2) Simulation with air in a cell equal to the active volume of the dosemeter, and the point source. The cell filled with air was placed at the same point as the active volume, and within this reference volume the volume-averaged neutron fluence per source-emitted neutron was calculated.

2.3.3. Neutron source. The neutron source considered in each position is in agreement with neutron spectra reached in previous works [García-Fernandez et al., 2020c, 2021].

2.3.4. Ambient dose equivalent. As aforementioned, in agreement with ICRU/ICRP, the operational quantity for reference was the ambient dose equivalent, $H^*(10)$, reached through the convolution of neutron fluence, $\Phi(E)$, cm$^{-2}$, and the ICRU fluence to ambient dose equivalent conversion function, $h(E)$, Sv·cm$^2$. $H^*(10)_{ref}$ has been calculated simulating three different types of neutron REM-meters, WENDI, LUPIN and PRESCILA, as the same places in proton center as the personal dosemeters.

2.3.5. MCNP6 settings and calculations. The dosemeter verifications were carried out by estimating $H^*(10)_{ref}$ and $H_p(10)_{cal}$ at different the points of interest using the MC code MCNP6® version 6.2. [Werner, 2017]. ENDF, evaluated nuclear data libraries, La150n library, were used up to 150 MeV [Chadwick et al., 2011], and nuclear models above that energy, the CEM03.03 model for intra nuclear cascade reactions (INC), and the GEM model for evaporation (EVM). The number of histories carried out was $10^9$, to achieve a statistical uncertainty under 5%, considering 20 energy groups (from $10^{-9}$ to 230 MeV). As variance reduction in cells of the dosemeters, biasing methods and weight factors were used based on geometry splitting and Russian roulette. Tallies used were F2, F4 with FM4 multiplier, and finally F6.
3. – RESULTS

3.1. – Dosemeters response and local correction factors in CPTC

Local corrections factors (LCFs) at different points in a CPTC, by dividing \( H_p(10)_{\text{cal}} \) between \( H*(10)_{\text{ref}} \), are collected in Table 1.

Table 1: Simulated response of neutron dosemeters and LCFs in CPTC

<table>
<thead>
<tr>
<th>CPTC</th>
<th>W-a inside</th>
<th>W-a outside</th>
<th>S-g inside</th>
<th>S-g outside</th>
<th>TCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_p(10)<em>{\text{cal}}/H_p(10)</em>{\text{ref}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Active - APDs</strong></td>
<td>8.4</td>
<td>8.9</td>
<td>3.2</td>
<td>4.7</td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Passive – Albedo (TLD)</strong></td>
<td>2.7</td>
<td>1.5</td>
<td>1.2</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Passive – Track etch</strong></td>
<td>0.7</td>
<td>2.9</td>
<td>0.8</td>
<td>1.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Looking at the results, the active dosemeters, APDs, strongly overestimate the response with respect to the \( H*(10) \) in CPTC, for all energies considered. For high energies (points inside the shielding), the overestimation is greater with higher energy neutrons, 8.4 in W-a-I versus 3.2 in S-g-I. For low energies (points outside the shield), the lower is the neutron energy, the greater is overestimation. Thus, in TCR with very low energy neutrons the LCFs is almost 10, 9.6, while in S-g-O, with neutron at intermediate energy, is 4.7. The energy of the neutrons inside and outside the shielding is collected in Figure 7 for the positions W-a-I and W-a-O, respectively.

In CPTC, passive albedo-type dosemeter also overestimate \( H*(10) \), but in a milder way than APDs, with factors from 2.7 for high energy neutrons (W-a-I), up to 1.3 in TCR, when the neutrons are highly thermalized, and their energy is low.

Finally, the behaviour of passive track etch-type is oscillating and does not follow a continuous pattern like the previous two. Observing the data in Table 1, there is an
underestimation in the response for high-energy neutrons (inside the shielding), with values between 0.7 in the accelerator zone and 0.8 in the room zone. On the other hand, for thermalized neutrons there is an overestimation from 2.9 to 1.9.

3.2. – Dosemeters response and local correction factors in MPTC

Local correction factors (LCFs) at different points in a MPTC are collected in Table 2. In MPTC, the response of APDs highly overestimates $H^*(10)$ for all energies considered, but below the overestimation in CPTC. For high energies (points 1 and 4 inside the shielding), the overestimation is 3.1, in front of the snout of the FBTR, and at a distance of 1 m of the phantom, while in position 4, at a distance of 1.8 m of the phantom and 90 degrees from the proton beam in the snout is 2.4.

Table 2: Simulated response of neutron dosemeters and LCFs in in FBTR of RPTC

<table>
<thead>
<tr>
<th>MPTC-FBTR</th>
<th>$H_p(10)<em>{cal}/H_p(10)</em>{ref}$</th>
<th>TR1</th>
<th>TCTR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active – APDs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.1</td>
<td>4.4</td>
<td>7.1</td>
</tr>
<tr>
<td>4</td>
<td>2.4</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td><strong>Passive – Albedo (TLD)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>1.2</td>
<td>3.9</td>
</tr>
<tr>
<td><strong>Passive – Track etch</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>0.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>

On the other hand, for neutron with low energy, positions TR1 and TCTR, outside the treatment room, with a high degree of shielding, the lower the energy, the higher the overestimation. LCFs of 4.4 in TR1, with one barrier, while in TCTR with two walls between source and the position of measurement, the overestimation reached 7.1. The energy of the neutrons inside the shielding, at different angles from snout, is collected in Figure 9 for the positions 1 to 4, for an IMPT treatment with an SOBP (Spread-Out Bragg Peak) 141.7 to 82.3 MeV.

In MPTC, passive albedo-type dosemeter follow the same patron as CPTC, overestimating $H^*(10)$, with factors from 3.9 for low energy neutrons (TCTR), up to 1.2 in TC1. Inside
the treatment room, with high energy neutrons the overestimation is between 1.4 and 1.6, which implies that it increases when the energy of the neutrons decreases.

Finally, the passive track etch-type in MPTC underestimates the response for all values except for very low energy neutrons, at TCTR, where there is an overestimation of 2.8. Therefore, they do not follow the same pattern as in CPTC, where there is underestimation inside the shielding and overestimation outside.

3.3. – Benchmark with data records

To verify the precision of the calculations achieved, the results corresponding to CPTC have been compared with real data [Herault and Carnicer, 2018], recorded from the radiological protection service of a compact center in operation. These real data are shown in Figure 14, reaching a maximum of 0.3 mSv/year, corresponding to the position of medical physician, against technical staff and maintenance of the accelerator, as could be considered at first. The reason could be that technical staff are more careful with radiological protection, since they work in more dangerous environments.

![Annual mean dose](image)

Figure 14.- CPTC annual mean dose recorded [Herault and Carnicer, 2018]
Table 3: Simulated response of neutron dosimeters and LCFs in FBTR of RPTC

<table>
<thead>
<tr>
<th></th>
<th>CPTC</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>$H_{p}(10)_{\text{annual}}$ (mSv)</td>
<td>Maximum (mSv)</td>
<td></td>
</tr>
<tr>
<td>Active - APDs</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>Passive - Albedo</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Passive – Track etch</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Data record</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

The mean annual dose for a CPTC calculated by MCNP6 for different dosimeters are shown in Table 3. The results reached show a large overestimation, by a factor from 6.3 (track etch) to 41 (APDs), depending on the dosemeter, and a factor of 21.3 for passive albedo systems. Therefore, the more precise dosemeter would be the passive track etch.

4. – DISCUSSION

Preliminary results carried out through MCNP6.2 Monte Carlo code simulations at several points of both, CPTC and MPTV facilities, show that track detectors underestimate response of neutrons at high-energy, albedo passive systems have a slightly over-response for all the energies, while APDs greatly overestimates response for all the energy of neutrons.

Regarding the annual dose, comparing with real recorded data, the more precise dosemeter would be the passive track etch, with an overestimation near 6.3. However, APDs would overestimate the annual dose by a factor of 41, while the overestimation with albedo passive dosemeters would be a factor of 21.3.

The radiation fields stated are essential to design the measures of operational radiological protection like selecting the radiation detection devices and the REM-meters for high energy neutrons and its location in the center, developing the radiological monitoring of the
areas, the classification and requirements of the different radiological zones, the establishment of radiation monitoring programs by calculating the derived levels, and to establish dosimetric surveillance measures for exposed personnel, with full guarantee and compliance of the limits of doses for professionals, clinical staff and general public. Considering the results of this work, and in previous works of the same project, a proposal with ten main considerations about operational radiological protection was listed below.

1. Suitable barriers and shielding against neutron radiation is essential in accelerator treatment room (or two rooms in compact facilities with synchrotron), and control rooms to limit doses to staff.
2. The design of this shielding could be based on Monte Carlo simulations, however, validation and estimation of doses of exposed workers by measurements with portable neutron and gamma devices should be carried out in commissioning stages.
   a. Uncertainty in physics models and nuclear data library in MCNP could vary from 1.3 to 1.9, depending on the model and the library.
   b. In benchmark with MPTC, radiation density in CPTC with synchrocyclotron is 2 mSv/Gy, approximately. Between 2% and 5% higher.
3. From the point of view of activation, the most recommended concretes are those with the lowest content of impurities that can be activated and generate radioactive waste. From an attenuation point of view, however, concretes of high density (with magnetite) or with high hydrogen content (with colemanite) are more efficient. Conventional Portland-type concrete has an intermediate activation and attenuation behaviour, and its building cost is more profitable than with special concretes.
4. Considering that the flux and the neutron spectrum varies significantly in each area of the installation, it would be advisable to use different concretes, optimizing the selection with criteria based on attenuation, activation and the cost of building.
5. Uncertainty in material composition and properties is a critical data in attenuation and activation:
   a. Percentage of H in conventional cement could be between 0.4% to 2.1%.
   b. Density of conventional concrete varies between 2.3 and 2.4 g/cm³.
c. Collect data of material along building of facility is a key task in commissioning process.

6. It is necessary to place neutron and gamma detectors at critical points of the facility to monitor dose rates, neutrons fields from protons interactions and gamma radiation from activation. Uncertainty in monitors and REM-meters response could vary from 3% to 10%, depending on energy and angle.

7. It would be necessary portable devices for gamma, neutron and contamination detection, in order to check different elements of the facility, as ground water, HVAC water, air or metallic elements.

8. Personal neutron dosemeters should be used for both, medical and technical staff. There are different types, but gamma dosemeters and neutron dosemeters would be mandatory. For some operations of technical staff in acceleration room would be advisable ring dosemeters and active personal dosemeters (APDs).
   a. Track dosemeters underestimate high-energy neutrons.
   b. Albedo dosemeters have a slightly over-response for all energies
   c. Electronic dosemeters have a large overestimation for all energies.

9. Both, ambient monitors and personal dosemeters should be able to measure neutrons in a large range spectrum, from thermal, $10^{-9}$ MeV, to high energies, 230 MeV.

10. Neutron field characterization (energy and angle) should be carried out, in order to state specific facility and local correction factors (LCFs), using proper devices (Bonner spheres, slab phantom).

5. - CONCLUSIONS

The characterization and to assessment of the performance of different personal neutron dosemeters, through the Monte Carlo codes, MCNP6 and GEANT4, for use in proton therapy centers. Three different types of personal dosimeters have been simulated, albedo passive dosemeter with TLD, passive dosemeter track etch and finally active electronic dosemeter. The personal dose equivalent, $H_p(10)_{cal}$ reached with personal dosemeters has
been compared with ambient dose equivalent, H*(10)_{ref}, in two different types of proton centers, one compact (CPTC) and one with multiple rooms (MPTC). H*(10)_{ref} used as dose of reference, has been calculated simulating three different types of neutron REM-meters, WENDI, LUPIN and PRESCILA, as the same places as the personal dosemeters. Finally, local corrections factors have been achieved, depending on the type of center and the type of dosimeter by dividing Hp(10)_{cal} between H*(10)_{ref}. Absolute response of neutron REM-meters used in the work had been characterized in previous works of the same research project, WENDI and LUPIN through MCNP6 code and Prescilla using GEANt4 Monte Carlo code.

Track detectors underestimate response of neutrons at high-energy, albedo systems have a slightly over-response for all the energies, while APDs greatly overestimates response always. Regarding the annual dose, comparing with real recorded data, the more precise dosemeter would be the passive track etch, with an overestimation near 6.3. However, APDs would overestimate the annual dose by a factor of 41, while the overestimation with albedo passive dosemeters would be a factor of 21.3.

There are large sources of uncertainty in the model of personal dosemeters, as the energy response, sensitivity, or orientation, among others, therefore, results in the work should be compared with experimental measurements during commissioning of the center.

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