Design of radiological area monitoring in compact proton therapy centers (CPTC)
(Operational Radiation Protection in CPTC)

Gonzalo F. García-Fernandez[1,2*], Eduardo Gallego[1], José Mª Gómez-Ros[3], Héctor R. Vega-Carrillo[4], Karen A. Guzman-García[4], Roberto García-Baonza[1], Lenin E. Cevallos-Robalino[5], Eduardo Fuentes Hernández[2]

[1]*Departamento de Ingeniería Energética, ETS Ing. Industriales, Universidad Politécnica de Madrid (UPM)*
C. José Gutiérrez Abascal 2, 28006, Madrid, Spain.
[2]*Biología y Técnica de la Radiación, S.L. (Bioterra, S.L.)*
Camino de los Perdigones 2, 28224, Pozuelo de Alarcón, Madrid, Spain.
[3]*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)*
Avda Complutense 22, 28040 Madrid, Spain.
[4]*Unidad Académica de Estudios Nucleares, Universidad Autónoma de Zacatecas*
C. Ciprés, 10, 98060 Zacatecas, México.
[5]*Grupo de Investigación en Sistemas de Control y Robótica, GISCOR, Universidad Politécnica Salesiana*
C. Robles 107 Chambers, 090108, Guayas, Guayaquil, Ecuador.

*Corresponding author's e-mail: gf.garcia@upm.es

Abstract. The advantages of proton therapy (PT) in some treatments again cancer have led to a significant expansion of proton therapy centers (PTC) around the world, with almost one hundred working nowadays. The current trends are to build small compact and standard facilities, along with the renovation of the multiple room centers (MPTC) built in the early stages of PT. Compact Proton Therapy Centers (CPTC), usually with one treatment room, sometimes two, act out latest advances in particles therapy. In the interaction of protons with elements of the facility, a huge production of stray radiation is yielded, neutron and gamma mostly, therefore optimal design of radiological area monitoring must be developed and carried out in commissioning stages. The aim of this work was to design the operational radiological protection in a compact proton therapy center (CPTC), by selecting the radiation detection devices and the REM-meters for high energy neutrons, as well as its location in the center, to develop the radiological monitoring of the area, with full guarantee and compliance of the limits of doses for professionals, clinical staff and the general public. Several models of the radiation sources and materials of facility were simulated, starting from a conservative assumption, followed by more realistic models. Evenly, the neutron fields and spectra present in the installation were characterized selecting the most appropriate radiation measurement device in each location. The work is framed into the project *Contributions to operational radiation protection and neutron dosimetry in compact proton therapy centers (CPTC)*.

KEYWORDS: Compact proton therapy centers; area monitoring, operational radiation protection.

1 INTRODUCTION

Based on International Basic Safety Standards and Regulatory Principles [1], main radiological risks in proton centers have been widely stated [2], and could be summarized in three key points:
1. External exposition to secondary radiation from beam line.
2. External exposition from activated equipment, materials of the facility, water and air.
3. Internal exposition for inhalation of radioisotopes in activated air.

Proton therapy is in continuous ever evolving to improve its performance. Some prominent current trends involve cutting-edge delivery methods or building compact proton centers [3]. New developments have direct impact in radiation protection of facilities [4]. Compact centers, however, have specific features to reduce their size while achieving more affordable facilities [5]: usually have one single room (sometimes two) and small footprint, higher radiation density, standard geometry, intensive use of new materials, advanced equipment and machinery, Pencil Beam Scanning (PBS) as delivery technique, mix of professional exposed workers (clinical and technical staff). These characteristics make compact centers face significant challenges, from the point of view of operational radiation protection [6].

This 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 these innovations on the operational radiation protection and commissioning of the compact proton facilities [7]. Thus, several tasks related to such project have been carried out over the last three years in fields as checking shielding [8], comparing ambient dose yielded by neutrons in several CPTC [9], analyzing activation in shielding with different types of concrete [10], characterizing wide range Rem-meters to measure neutron fields [11], studying new proton delivery techniques and their neutron fields yielded [12], or assessing personal dosemeters suitable for CPTC [13], among others.

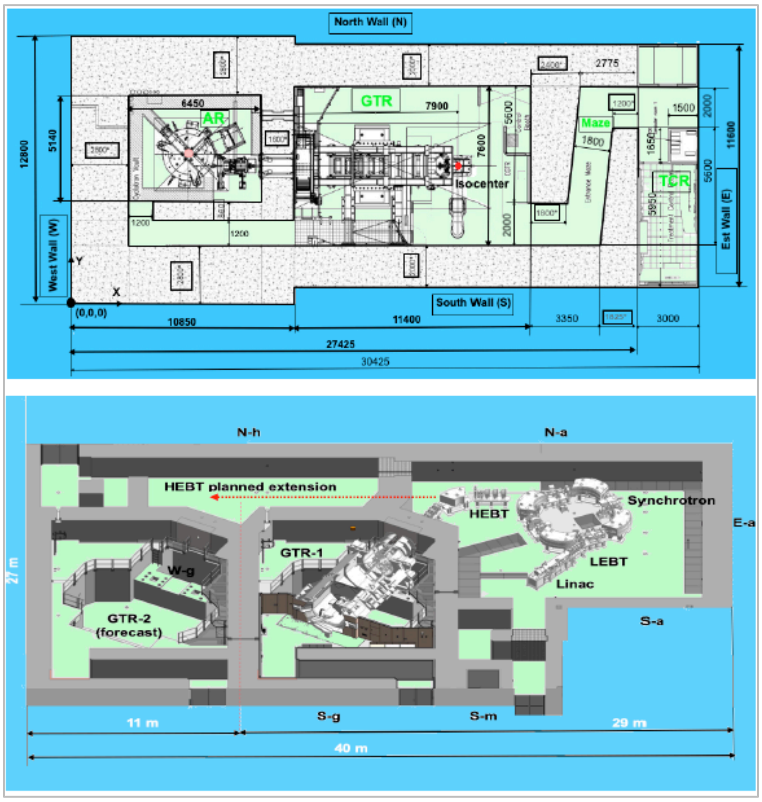
The aim of the work is to present those different activities developed from 2018 until now, in designing the operational radiological protection of compact proton therapy centers (CPTC), collecting outcomes achieved in the fields aforementioned, as the evaluation of shielding and ambient dose equivalent, H*(10), activation in barriers, activation in machinery, air and water, evaluation of rem-meters and ambient neutron monitors, comparison of neutron fields yielded with current and new proton delivery methods, or preliminary studies of neutron dosemeters fit to exposed personal in these centres. In Results, Section 3.6 gathers several actions proposed to develop the radiological monitoring of the area, with full guarantee and compliance of the dose limits for clinical staff, technical staff and general public.

As a result of these activities, a commissioning process of the operational radiation protection of CPTC will be suggested, line up with the requirements by Spanish Nuclear Authority (CSN). Containing, for instance, verification that shielding has been executed in compliance with initial request, certificate of materials with composition of cement and density of concrete, ambient detection and control system in operation, including the justification, limitation and optimization (ALARA) of actions proposed [14].

2 MATERIALS AND METHODS

The work is focused on the CPTC planned and currently working in Spain, shown in Fig. 1. The first one has a synchrocyclotron accelerator with extraction energy fixed at 230 MeV, and the second one has a synchrotron accelerator, and extraction energy adjustable between 70 and 230 MeV.

Figure 1: Main features of CPTC studied, a) Top, with synchrocyclotron, b) Bottom, with synchrotron

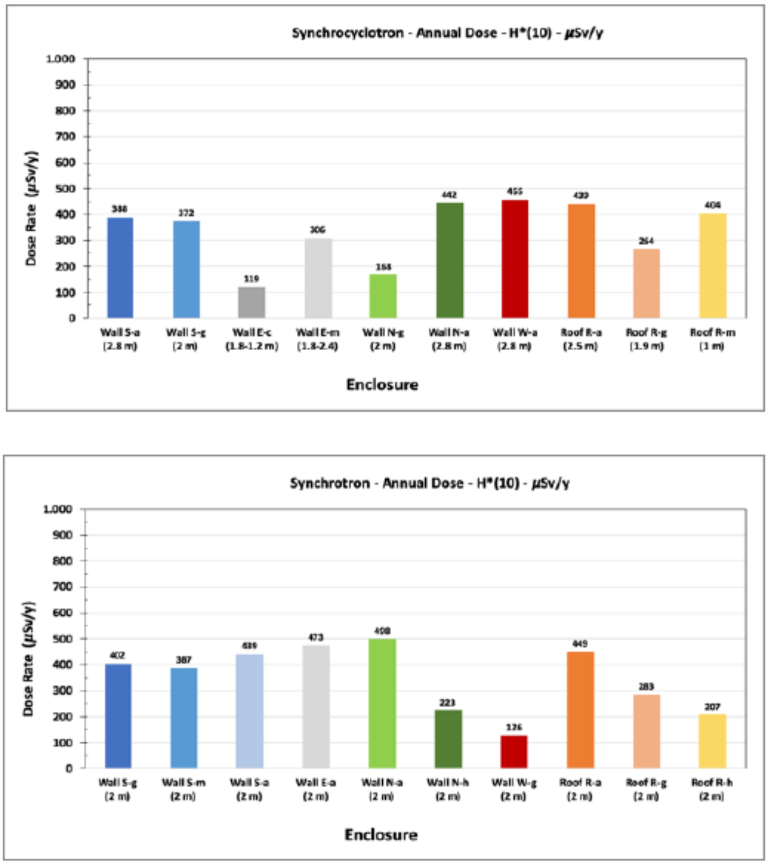


3 RESULTS AND DISCUSSION

3.1 Shielding design and Ambient Dose equivalent, H*(10)

First of all, effectiveness of shielding in CPTC was verified by calculating the ambient dose equivalent, H*(10) in uSv/year, due to secondary neutrons, outside the enclosures and walls. The facilities modelled, shown in Fig.1, had a standard configuration, and width of walls based on dimensions proposed a priori by the vendors, therefore, the study was focused on check the suitability of the materials and thickness of barriers. Several models of radiation sources and type of concrete in walls were simulated, starting from a conservative assumption, followed by more realistic hypothesis. The simulations were carried out using Monte Carlo (MC) code MCNP6® version 6.2, computing the fluences of secondary neutrons produced by interaction of the beam of protons in different points of the facilities. Full details of study in CPTC with synchrocyclotron are set out in [8], while details of the study in compact center with synchrotron, and benchmarking of both facilities, are collected in [9].

Figure 2: H*(10) behind walls of CPTC, a) Top, with synchrocyclotron, b) Bottom, with synchrotron



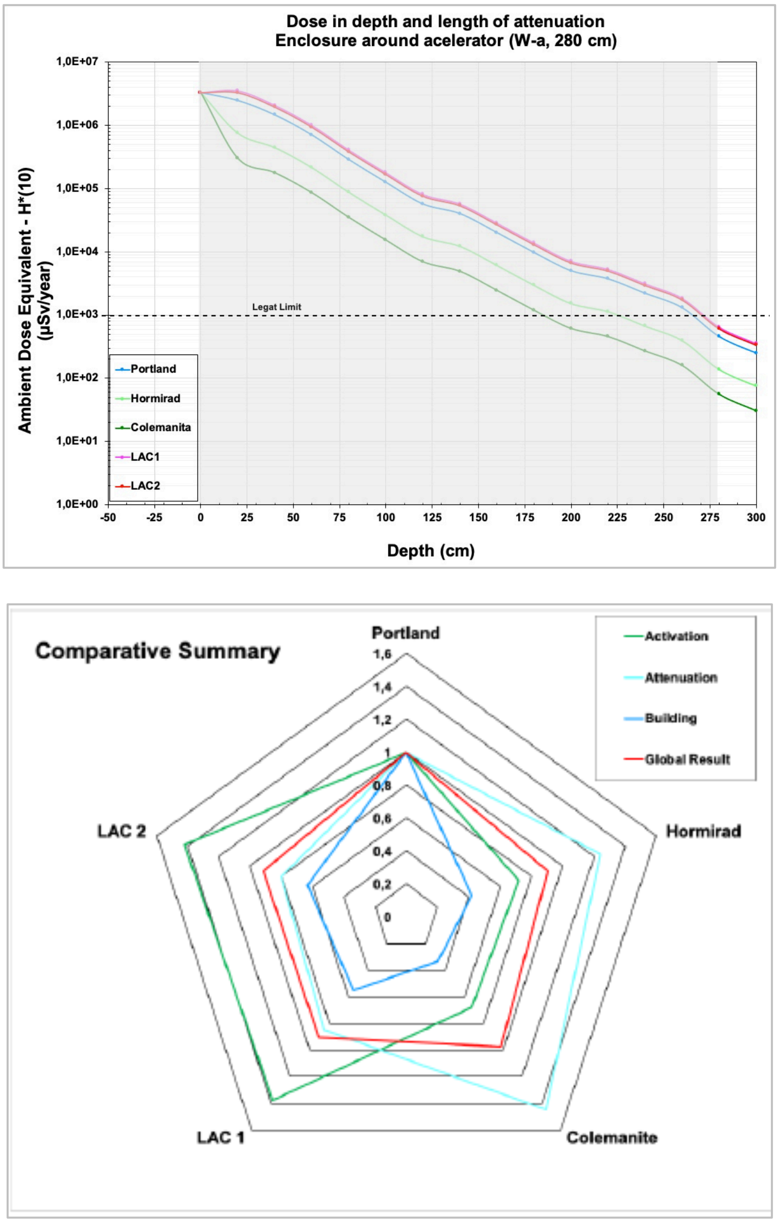
As shown in Fig. 2, in all cases, assuming the worst scenario, the results reached in both facilities were well below 1 mSv/year, which is the legal limit internationally accepted for the general public.

3.2 Neutron activation and materials in barriers

The next task was to carry out a comparative analysis, using the MCNP6 code, of neutron activation in CPTC facilities with synchrocyclotron [10]. Five different types of concrete were studied: conventional portland concrete, hormirad® (high density concrete with magnetite), colemanite (borated concrete with a high percentage of hydrogen), and finally two different low activation concretes (LAC), called LAC1® and LAC2®, respectively. Characteristics of materials studied are collected in [8-10] and [15, 16]. Considering the energy reached by neutrons, up to 230 MeV, four different libraries were used, ENDF/B VII.1, JEFF-3.3 and TENDL2017/19, in order to study the sensitivity of results to nuclear data.

The attenuation plot with different types of concrete and the comparative summary are shown in Fig. 3. From activation point of view, the most recommended concretes are those with the lowest content of impurities that can be activated and generate radioactive waste, LAC1 and LAC2. 2. From the attenuation point of view, however, concretes of high density (with magnetite) or with high content of hydrogen (with colemanite) are more efficient. Conventional Portland-type concrete has an intermediate activation and attenuation behaviour, and its building cost is more profitable than other special concretes. In summary, considering that both, flux and neutron spectrum varies significantly in each area of the facility, it would be advisable to use different concretes for each area, optimizing the selection with criteria based on attenuation, activation and the cost of building. Further results, and studies of activation in metallic parts, elements of the facility, water and air are collected equally in [10].

Figure 3: a) Top, attenuation plot with different concretes, b) Bottom, Comparative summary

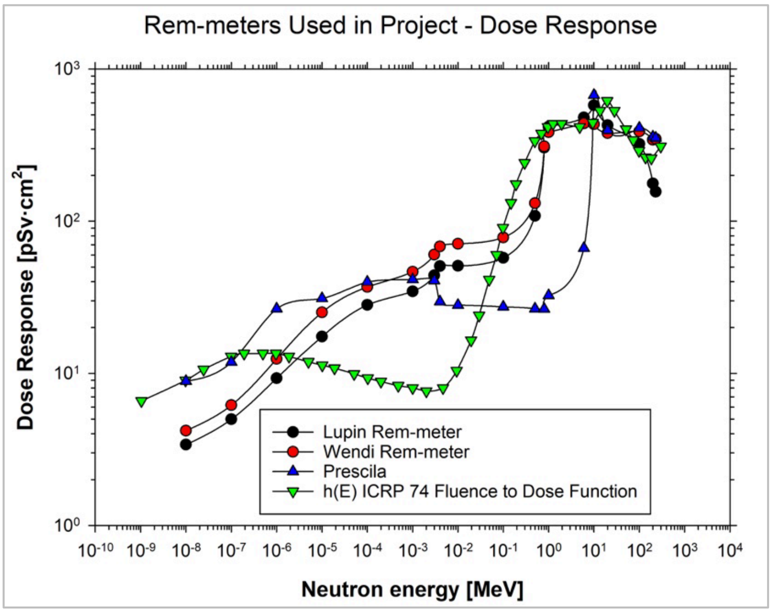


3.3 Rem-meters and ambient neutron monitors

In the same way, the analyse and evaluation of the response of several extended range neutron REM-meters, was carried out. WENDI-II, LUPIN and PRESCILA devices, respectively, were characterized through the Monte Carlo code MCNP6, for their application in shielding and radiation area monitoring in CPTC facilities. Further details of the process are included in [11, 12].

The main results reached were both, absolute response and dose response of REM-meters, as a function of neutron energy, as shown in Fig. 4 for dose response. Once characterized, the monitors are being used in operational radiation protection, along with experimental measurements in several proton therapy facilities [11, 12]. Likewise, response of extended-range Bonner Sphere (SSB) was caried out [17].

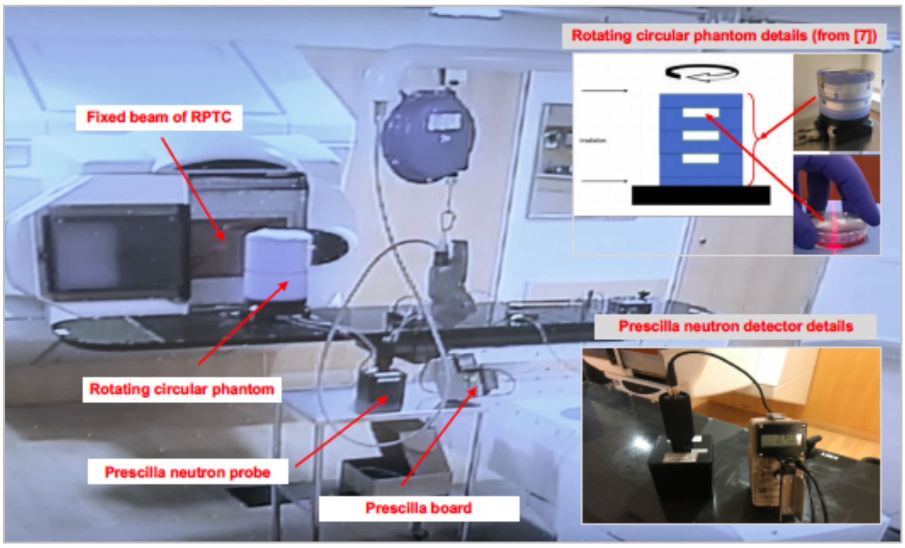
Figure 4: Dose response of REM-meters characterized: WENDI-II, LUPIN and PRESCILA



3.4 Comparing neutron fields of new delivery methods in proton therapy

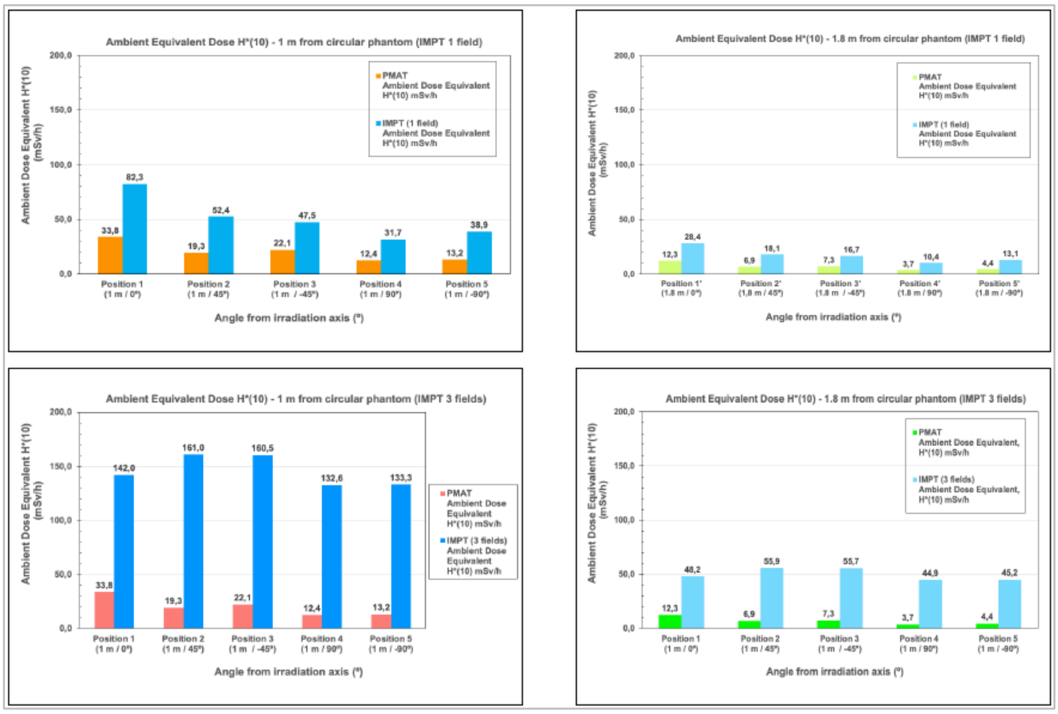
Proton monoenergetic arc therapy (PMAT) is a new delivery modality, currently in research and at development stages by Prof. Carabe-Fernández, which aims to take advantage of irradiation of the tumour volume under fields with a full 360º angle, using monoenergetic protons and optimizing the LET inside the target [18]. Experimental measurements, using PRESCILA detector, of neutronic fields yielded with proton monoenergetic arc therapy (PMAT), were compared with those generated with the conventional intensity-modulated proton therapy (IMPT) treatment, at different distances and angles of the circular phantom used in the radiobiological experiment [18]. The measurements were carried out at the Fixed Beam (FBTR) of the Roberts Proton Therapy Center (RPTC) in the Hospital of University of Pennsylvania (UPenn). Experimental set-up is shown in Fig. 5, with fully details collected in [12].

Figure 5: Experimental set-up at FBTR (Fixed Beam Treatment Room) of RPTC in UPenn



As shown in Fig. 6, H*(10) is in the same order of magnitude with both modalities, but with PMAT is lower than with IMPT, almost three times. Likewise, simulations carried out with MCNP6.2 code were compared with experimental measurements. PMAT would have dosimetric advantages and optimization of LET, at the same time that would achieve a not negligible reduction of secondary neutrons [12].

Figure 6: H*(10) with PMAT vs. IMPT: a) Left, at 1 m from isocenter, b) Right, at 1.8 m



3.5 Personal dosemeters

At present, it is being carried out the assessment of several personal neutron dosemeters to use in proton therapy centers, considering the challenges in this field [19]. Dosemeter characterized are several passive devices (TLD and track), included in the most recent EURADOS report [20], and active (DLD).

Preliminary results carried out through MCNP6.2 Monte Carlo code simulations at several points of both, CPTC and MPTV facilities, are collected in Table 1. Track detectors underestimate response of neutrons at high-energy, albedo systems have a slightly over-response for all the energies, while DLD greatly overestimates response always. In [13], simulations were compared with real data from a CPTC facility [21], showing a large overestimation, between 6 to 40, depending on the dosemeter.

Table 1: Simulated response of neutron dosemeters: a) Up, in CPTC, b) Bottom, in FBTR of RPTC

CPTC					
$H_p(10)_{cal}/H_p(10)_{ref}$	W-a inside	W-a outside	S-g inside	S-g outside	TCR
Active - DLD	8.4	8.9	3.2	4.7	9.6
Passive – Albedo (TLD)	2.7	1.5	1.2	1.8	1.3
Passive – Track	0.7	2.9	0.8	1.6	2.4

MPTC-FBTR				
$H_p(10)_{cal}/H_p(10)_{ref}$	1	4	TR1	TCTR
Active - DLD	3.1	2.4	4.4	7.1
Passive – Albedo (TLD)	1.4	1.6	1.2	3.9
Passive – Track	0.9	0.8	0.8	2.8

3.6 Design of the operational radiation protection in CPTC

Based on the tasks and results obtained in the activities indicated above, the following ten recommendations could be established in the design of operational radiation protection in CPTC:

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/cm^3.
    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 devices (DLD).
    a. Track dosemeters underestimate high-energy neutrons but underestimate at low energy.
    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 (LCF), using proper devices (Bonner spheres, slab phantom).

4 CONCLUSIONS

The design of operational radiation protection of Compact Proton Therapy Centers (CPTC) was developed in this work, collecting activities from 2018 until now. Main outcomes include evaluation of shielding and ambient dose equivalent, H*(10), activation in barriers, machinery, air and water, evaluation of ambient neutron monitors, comparison of neutron fields yielded with current and new proton delivery methods, or preliminary studies of neutron dosemeters fit to exposed personal in these centres. In section 3.6, several actions are proposed to develop the radiological monitoring of the area, with full guarantee and compliance of the dose limits for clinical staff, technical staff and general public.

As a result, a commissioning procedure of operational radiation protection in CPTC will be proposed, line up with the requirements by Spanish Nuclear Authority (CSN), including certificate of shielding, data of shielding checks and tests, certificate of materials, ambient detection and control system in operation, with justification, limitation and optimization (ALARA) action suggested.

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