Impact of new developments in the commissioning of operational radiation protection in Compact Proton Therapy Centers (CPTC)

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Abstract. 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. New developments have a direct impact in radiation protection of proton facilities and actions should be developed continuously with the aim that new centers meet all the requirements. The study of radiological protection in multi-room centers has been widely studied elsewhere, however, compact centers have specific features that pose a challenge in radiation protection, and the present work suggest different contributions to the body of knowledge in these compact facilities. Compact Proton Therapy Centers (CPTC) act out latest advances in particles: Usually have one single room, small footprint and a standard configuration, higher radiation density (Sv/m^2), using the most advanced equipment and machinery to reduce their size, the delivery mode of protons is Pencil Beam Scanning (PBS), and there is a mix of professional exposed workers (clinical and technical staff) in these centers.

The present 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 facilities. Thus, several tasks have been carried out over the last three years, as checking and evaluation of shielding, comparing ambient dose equivalent of several CPTC, analyzing activation with different types of concrete, and activation in machinery, air and water of the facility, characterizing wide range rem-meters and neutron area monitors to measure neutron fields, studying new proton delivery techniques and their neutron fields, or assessing personal dosemeters, among others. The aim of the work is to present outcomes achieved in the aforementioned areas. As a result, a commissioning process of the operational radiation protection in compact centers will be suggested, lined up with the requirements by the Spanish Regulatory Body.

Considering topics as new methods of application of dose in development (proton arc therapy, flash-therapy with protons), new materials for barriers and shielding or recent radiation monitoring equipment, future works must be carried out to study their impact on operational radiation protection and recommendations such as ICRP Publication 127, Radiological Protection in Ion Beam Radiotherapy, should be updated periodically considering the new methods and technologies developed.

Keywords: Compact proton therapy centers (CPTC); Proton new delivery modes; Operational radiation protection; ICRP Publication 127

1 Introduction

The advantages of proton therapy (PT) in some treatments against cancer have led to a significant expansion of proton therapy centers around the world, with almost one hundred in operation and over fifty at different stages of development. Current trends in PT are to build small compact and standard facilities, along with the renovation of large multiple room proton therapy centers (MPTC), laid down in the early stages of PT [1].

Based on International Basic Safety Standards and Regulatory Principles [2], main radiological risks in proton centers (PTC) have been widely stated and summarized [3]:

1. External exposure to secondary radiation (neutrons and photons) from beamline.

2. External exposure from activated equipment, materials of the facility, water and air.
3. Internal exposure for inhalation of radioisotopes in activated air.

Nevertheless, proton therapy is in continuous ever evolving to improve its performance and some prominent current trends involve cutting-edge delivery methods or building compact proton centers [4]. New developments have a direct impact in radiation protection of proton facilities and actions should be continuously developed to update the new requirements of centers [5]. Remarkable works about operational radiation protection design in MPTC are collected elsewhere [6-10]. Compact Proton Therapy Centers (CPTC), act out latest advances in particles therapy and have specific features to reduce their size while achieving more affordable facilities [11]. Consequently, from the point of view of operational radioprotection, CPTC face significant challenges [12]:

1. Usually these centers have one single room (sometimes two) and small footprint.
2. They have a higher radiation density in Sievert per square meter (Sv/m^2).
3. They have a standard geometry and configuration worldwide.
4. There is an intensive use of new materials and technology.
5. They use the most advanced equipment and machinery to reduce their size.
6. The usual delivery mode of protons is Pencil Beam Scanning (PBS).
7. There is a narrow mix of professional exposed workers (clinical and technical staff).

The present 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 [13]. Thus, several tasks have been carried out over the last three years, as checking and evaluation of shielding [14], comparing ambient dose equivalent of several CPTC [15], analyzing activation with different types of concrete, and activation in machinery, air and water of the facility [16], characterizing wide range rem-meters and neutron area monitors to measure neutron fields [17], studying new proton delivery techniques and their neutron fields [18], or assessing personal dosemeters [19], among others. The aim of the work is to present outcomes achieved in the aforementioned areas. As a result, a commissioning process of the operational radiation protection in CPTC will be suggested, lined up with the requirements by the Spanish Regulatory Body [20].

2 Material and methods

2.1 Compact proton therapy centers (CPTC) considered in the work

Although there are a wide range of commercial models of CPTC developed by different vendors, CPTC considered in this work are the standard version of the two centers in the first years of operation, being compact size both [13]. The first one, working from December 2019, has a cyclotron accelerator with extraction energy at 230 MeV and a footprint close to 360 m^2. The second one, working from May 2020, has a synchrotron accelerator, with extraction energy adjustable between 70 and 230 MeV and a footprint near 800 m^2. The standards CPTC modelled are made up of accelerator room (AR), treatment room with a compact rotating gantry (GTR) and the maze. Lay-out of the CPTC are shown in Figure 1 for synchrocyclotron (SC), and Figure 2 for synchrotron (SY). Further details are collected in [14, 15].

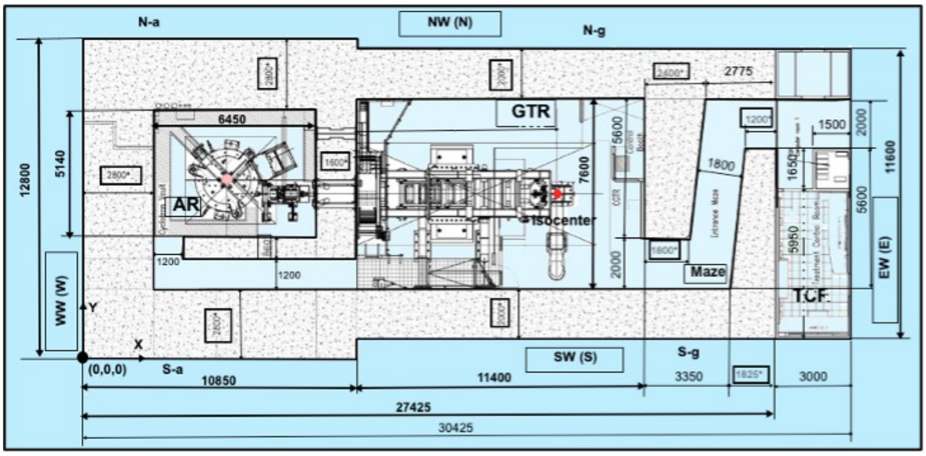


Fig. 1. Main features of CPTC with synchrocyclotron (SC).

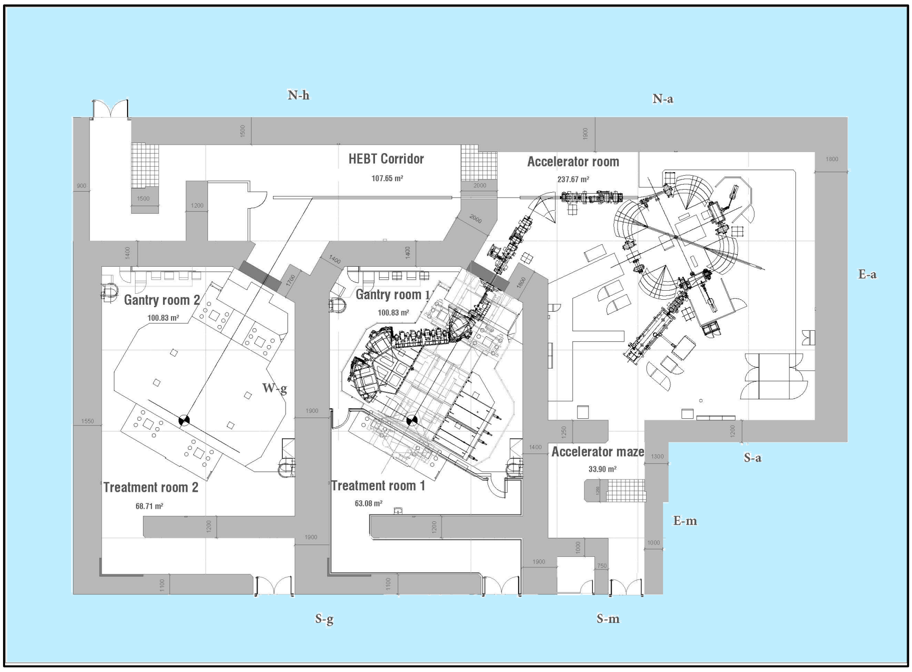


Fig. 2. Main features of CPTC with synchrotron (SY).

Both centers have three key elements: firstly, the accelerator, secondly the beamline (BL), and finally the Gantry Treatment Room (GTR). The general features of CPTC studied in this project are collected in Table 1.

Table 1: General features of CPTC considered in this work

Manufacturer	Model	Type of accelerator	Number of rooms	Footprint (m^2)
IBA	ProteusOne®	Synchrocyclotron (SC)	1	400
Hitachi	Expandable One Gantry System (EOGS)	Synchrotron (SY)	1 + (1)	800

From a point of view of generation of neutrons fields, considering the energy of proton beams, the delivery system of proton, the angle of rotation of the gantry and the type of beam, the main features or CPTC linked with stray radiation are collected in Table 2.

Table 2: Main features of CPTC with influence in neutron fields

Type of accelerator	Energy of protons	Beam Delivery System	Gantry Rotation	Proton Field
Synchrocyclotron (SC)	Fixed 230 MeV	PBS Pencil Beam Scanning	220º	Continuous (virtually, KHz)
Synchrotron (SY)	Adjustable 70 to 230 MeV	PBS Pencil Beam Scanning	360º	Pulsed (Hz)

2.2 Monte Carlo (MC) codes and settings

Facility design, equipment, and materials. The study of shielding verifications, activation in barriers, characterization of rem-meters and personal dosemeters, and comparing the neutron fields with different delivery methods, were carried out using the MC code MCNP6® versions 6.1 and 6.2 [21, 22]. The process to validate the shielding with the MCNP6.2 Monte Carlo code was developed in three main stages [23]: 1) Defining geometry, equipment, and radiation sources; 2) Modelling sources through a condensation process; 3) Shielding verification by estimating the ambient dose equivalent, H*(10) behind the enclosures of the CPTC. Features of main materials employed in MCNP6 were collected from [24]. In enclosures with influence in the shielding (walls and roofs), regular concrete, density, 2.3 g/cm^3 was tested. Calculation and hypothesis were based in data and information published in research works about synchrocyclotron systems [25] and synchrotrons systems [26].

Modelling all the components of the facility is neither viable nor useful from the point of view of the radiation sources. The method followed was the point neutron-equivalent in which the radiation sources are the points where proton beam losses interacting with matter [9]**.** A water phantom, with dimension of 40 x 40 x 40 cm^3, was considered as a patient, irradiated with a beam proton equal to the global efficiency at each energy [27]. The workload was estimated in agreement with data, in nA·h per year in each energy, at the exit of accelerator, assuming a conservative approach of 16-hour workday in two 8-hour shifts, six working days per week, and fifty weeks per year, 450 patients/year, 17.000 sessions, with 2 Gy/session, considering the clinical data about number of patients and typical treatment plans [28]. Occupancy factors were obtained from international recommendations by choosing the most conservative options [29]. The MCNP6 physics models chosen were the default options, the CEM03.03 model for intranuclear cascade (INC) followed by the GEM model for evaporation process (EVP), because the computation time is shorter, and the results are more conservative [30].

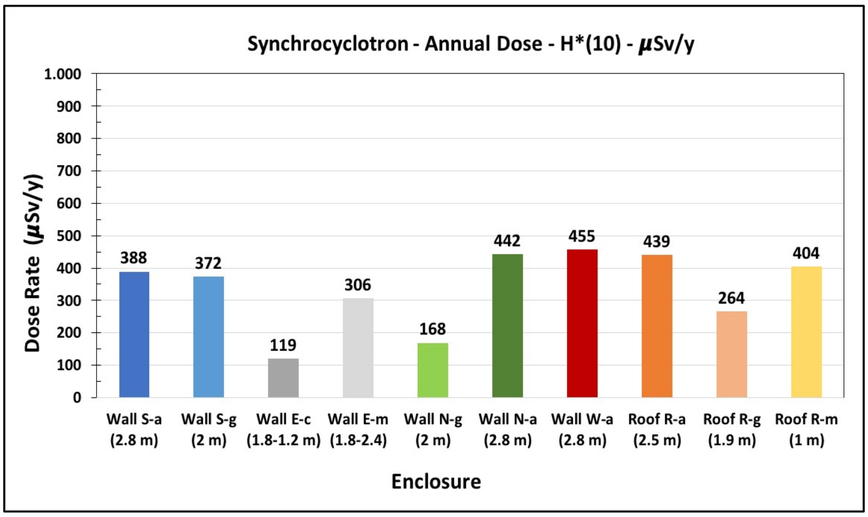
Area monitoring magnitude and personal dosimetry magnitude. In agreement with ICRU/ICRP, the operational quantity chosen was the ambient dose equivalent, H*(10), along the enclosures of the center, because is a conservative magnitude [31]. H*(10) was obtained through the convolution of neutron fluence, Φ(E), in cm^{-2}, and the ICRU fluence to ambient dose equivalent conversion function, h(E), in Sievert per square centimetres, $Sv \cdot cm^2$ [32], and its expansion above 201 MeV [33]. These coefficients 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. In personal dosimetry, the operational quantity used for external irradiation is the personal dose equivalent, Hp(d), which provides a reasonable overestimation of the limiting quantities and can be measured with relatively simple instrumentation. Hp(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.

MCNP6 settings and calculations. Simulations were carried out considering 20 energy groups (from 10^{-9} to 230 MeV), with a number of histories quite enough to achieve statistical uncertainties under 3%, verifying the ten statistical checks in MCNP [22]. ENDF/B (version VII.1), evaluated nuclear data libraries, La150n library, were used up to 150 MeV [34, 35], and nuclear models above that energy. GEM03.03 Model for INC reactions, and GEM Model for EVM process. To study the sensitivity of simulations and results to nuclear data, some works have been reached using two further libraries: 1) JEFF (version 3.3), which is jointly managed by the Joint European File (JEF) and the European Fusion File (EFF) groups [36]. 2) TENDL 2017 and 2019 libraries, Tallys Evaluated Nuclear Data Library [37]. Thermal treatments, designed by $S(\alpha, \beta)$ in the MCNP code, have been used in all the simulations for all neutron energies [38]. All rooms were considered air-filled and void in the proton beam. The results were computed using superposed mesh tallies inside the facility, along the walls and roofs and outside the enclosures. As variance reduction in cells of the walls, roof and air in vaults, biasing methods and weight factors were used based on geometry splitting and Russian roulette [22].

3 Results

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

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 had a standard configuration, and width of walls based on dimensions proposed a priori by the vendors. Results are collected in Figure 3.



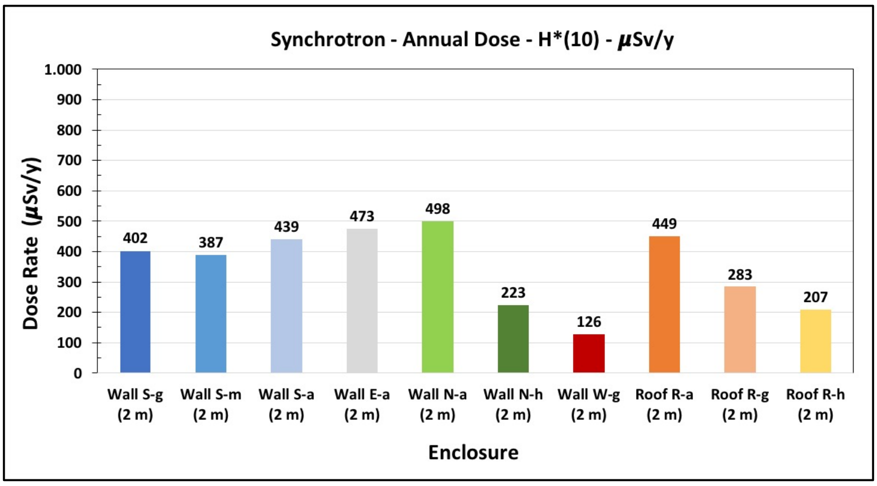


Figure 3: H*(10) behind walls of CPTC, a) Top, with SC, b) Bottom, with SY

In all cases, assuming the worst scenario, the values reached in both facilities were well below 1 mSv/year (millisievert per year), which is the legal limit internationally accepted for the general public. Although in both facilities, using different accelerators, the ambient dose equivalent to the public reached with the shielding considered is less than 0,5 mSv/y, a 50% under the maximum limit, the results are achieved with different wall thickness, approximately 2.8 m in Synchrocyclotrons, while in Synchrotrons the thickness of typical wall is 2 m. Several models of radiation sources and type of concrete in walls were simulated, starting from a conservative assumption (radiation sources in accelerator, energy selection system and phantom), 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 [14], while details of the study in compact center with synchrotron, and benchmarking of both facilities, are collected in [15].

3.2 Neutron activation and materials in barriers

The next task was to carry out a comparative analysis of neutron activation in CPTC facilities with synchrocyclotron, using the MCNP6 code [16]. Five different types of concrete were studied: conventional Portland concrete, hormirad® (high density concrete with magnetite), colemanite (concrete with a high percentage of hydrogen), and finally two new different low activation concretes (LAC), called LAC1® and LAC2®, respectively. Attenuation plot reached with different concretes is shown in Figure 4.

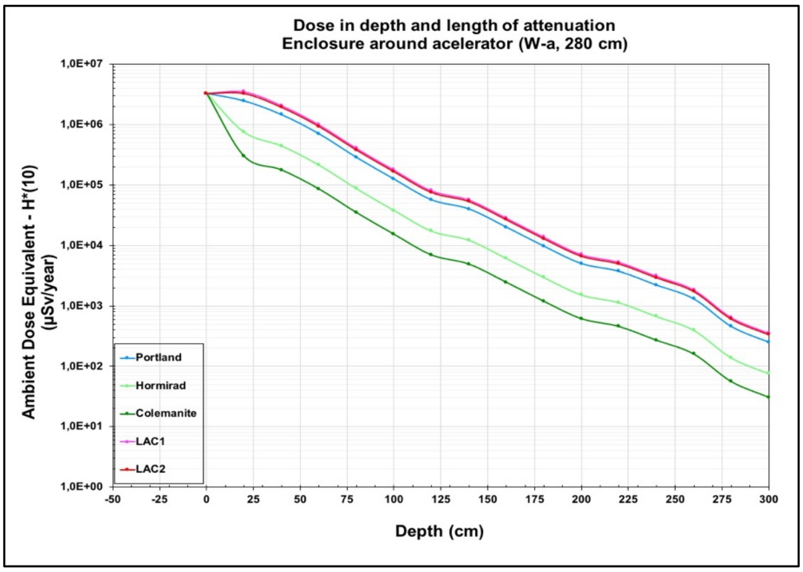


Figure 4: Attenuation plot with different concretes

Characteristics and composition of the materials studied are collected in [14-16] and [39, 40]. Considering the energy reached by neutrons, up to 230 MeV, four different neutron cross-section libraries were used, ENDF/B VII.1, JEFF-3.3 and TENDL2017/19, in order to study the sensitivity of results to nuclear data.

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 behavior, and its building cost is more profitable than with special concretes. The comparative summary of performance with different type of materials are collected in Figure 5.

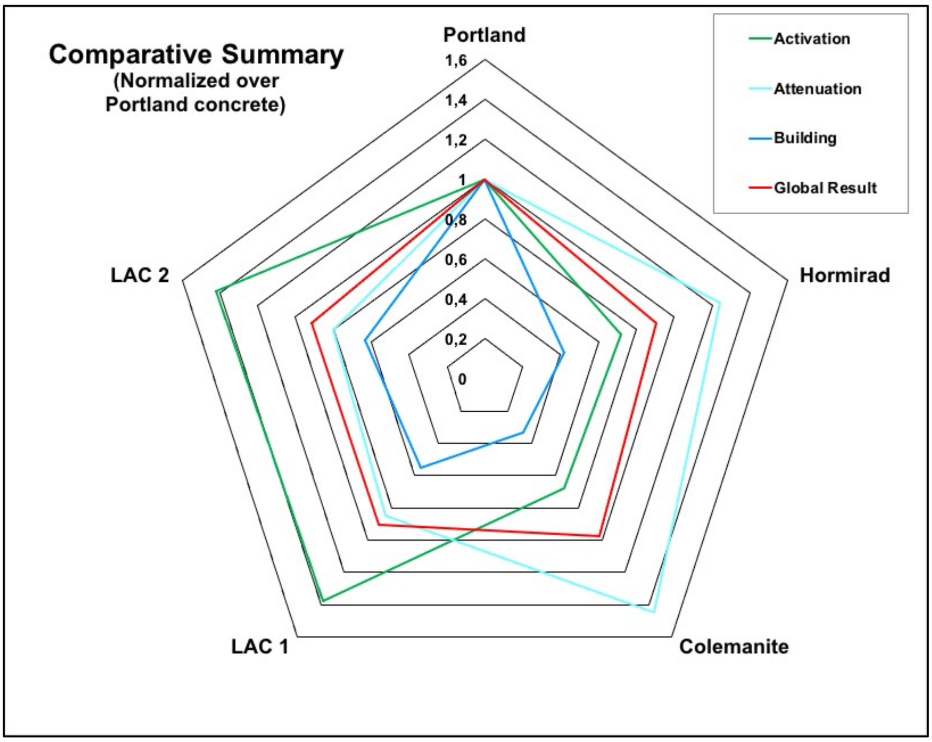


Figure 5: Comparative summary global performance with different concretes

In summary, it would be advisable to use different concretes for each area, depending on the neutron fluence expected neutron fluence in each wall, optimizing the selection with criteria based on attenuation, activation and the cost of building. The barriers with the highest fluence are those around the accelerator and the wall in front of the beam, in the treatment room. Further results, and studies of activation in metallic parts and mechanical elements of the facility, water and air are reported equally in [16].

3.3 Rem-meters and Neutron area monitors

The radiological monitoring of proton therapy centers requires using appropriate neutron measurements instruments of extended energy range. The analysis and response evaluation of several extended range neutron rem-meters and neutron area monitors were carried out, and WENDI-II, LUPIN-II and PRESCILA devices were characterized through the Monte Carlo code MCNP6, for their application in shielding and radiation area monitoring in CPTC facilities.

WENDI-II [41], Wide Energy Neutron Detection Instrument, is a rem-meter, type Anderson-Braun (A-B). LUPIN-II [42], Long Interval, Ultra-Wide dynamic, Pile-up free, Neutron rem-counter, is also a rem-meter, type Anderson-Braun (A-B). Finally, PRESCILA, Proton recoil Scintillator-Los Alamos [43], is a device, type scintillator, developed by los Alamos National Laboratory. Further details of the process are included in [17, 18]. The fluence-to-Ambient dose conversion coefficients, h(E), and the Ambient dose equivalent responses of these rem-meters are shown in Figure 6.

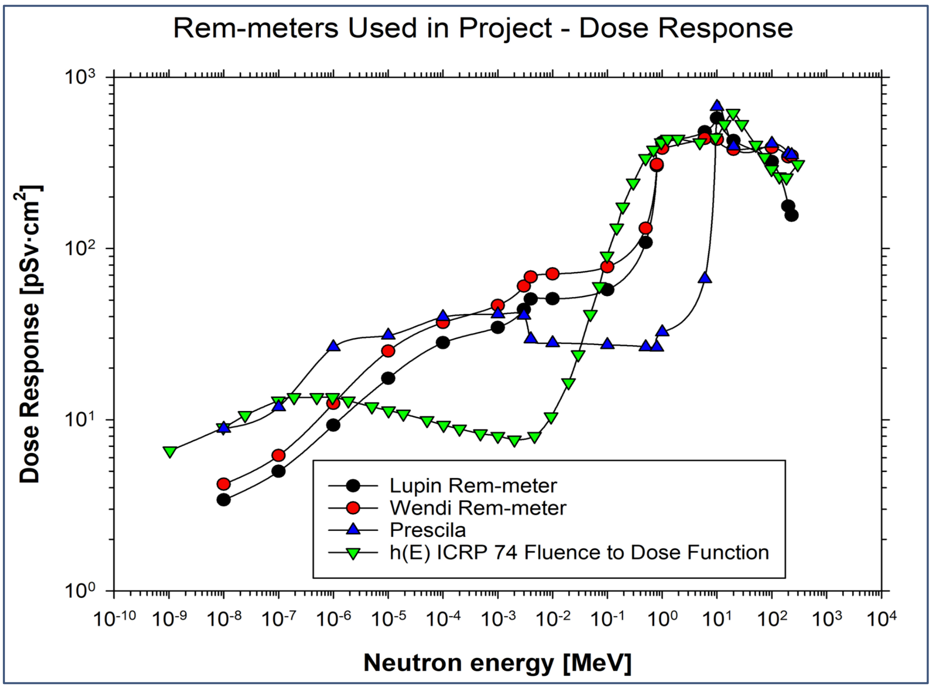


Figure 6: Dose response of REM-meters characterized in the work

Once characterized, these monitors were used in several proton therapy facilities [17, 18]. Likewise, to characterize the neutron spectrum is such facilities, it would be useful to use extended-range Bonner Sphere systems (BSS); the response of one of such BSS was carried out as described in [44].

3.4 Comparing neutron fields of new delivery methods in proton therapy

Proton monoenergetic arc therapy (PMAT) is a new delivery modality, currently at development stages by Prof. Carabe-Fernández [45], which aims to take advantage of irradiation of the tumor volume under fields with a full 360º angle, using monoenergetic protons and optimizing the LET (Linear Energy Transfer) inside the target [46].

Experimental measurements, using a PRESCILA detector, of neutronic fields yielded with 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 [46]. The measurements were carried out at the Fixed Beam Treatment Room (FBTR) of the Roberts Proton Therapy Center (RPTC) in the Hospital of University of Pennsylvania (UPenn). The experimental set-up is shown in Figure 7, with fully details collected in [18].

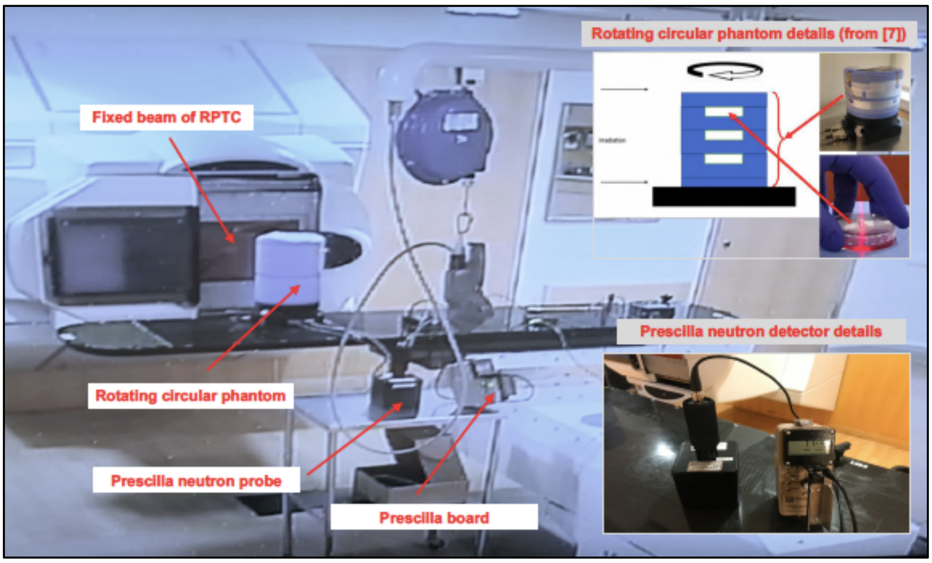


Figure 7: Experimental set-up at FBTR (Fixed Beam Treatment Room) of RPTC

Results show that, inside the treatment room, H*(10) with both modalities is within the same order of magnitude, however, the dose with PMAT is almost three times lower than with IMPT. Likewise, simulations carried out with MCNP6.2 code were compared with experimental measurements. To conclude, PMAT would have dosimetric advantages and optimization of LET, at the same time that would achieve a not negligible reduction of secondary neutrons [18].

4 Discussion and conclusions

Despite of the large and exhaustive studies developed in the implementation of radiological protection measures in proton therapy facilities, some of them mentioned in this project, protontherapy discipline is constantly evolving and incorporating new developments that pose a great challenge for radiation protection of patients, medical staff, exposed workers and the general public.

Therefore, when it is come to speak about the design of the operational radiation protection in moderns CPTC, based on the main results achieved in the several tasks mentioned above throughout this survey, some basic premises could be established, as a summary of the work, collected below in ten recommendations:

1. Suitable barriers and shielding against neutron and gamma stray radiation are essential in both, accelerator and treatment room (or rooms in facilities with compact synchrotron), and control rooms, to limit doses to staff and general public. Although gamma radiation is also yielded, its order of magnitude is much lower than neutron radiation.
2. The design of the mandatory 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. The results, achieved in several task of this work tied with checking of shielding in CPTC, show:
    a. Uncertainty in physics models and nuclear data library in MCNP could vary from 1.3 to 1.9, depending on the physic model and the nuclear data library employed.
    b. Radiation density achieved in the works mentioned in the paper corresponding to CPTC with synchrocyclotron is approximately 2 mSv/Gy (Ambient dose equivalent per biological dose), what means between 2% and 5% higher in the benchmark carried out with MPTC. This is clear, since the footprint of MPTC centers is quite larger than in CPTC.
3. Regarding the materials in barriers, 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 real composition of cement and material of barriers is a critical data in calculation both, attenuation, and activation. Evenly, results achieved in this work linked with the study of activation in CPTC show:
    a. Percentage of hydrogen in conventional cement could vary between 0.4% to 2.1%. To estimate both, features of attenuation and activation of the barriers, it is essential to know, as accurate as possible, the real composition of the cement supplied in the building of the facility.
    b. Density of conventional concrete varies between 2.3 and 2.4 g/cm^3. In this case, the density should be also tested at different stages of the building of center, at the laboratory of materials. These checks could be carried out at the same time as mandatory tests to verify the bearing strength of concrete.
    c. Hence, collect data of main materials, cement and concrete, along the building of center is a key task in commissioning process of these facilities.
6. It would be necessary to place neutron and gamma detectors at critical points of the facility (near the accelerator and isocenter), to monitor dose rates, mainly neutrons stray fields from protons interactions in beamline and the patients, and gamma radiation from activation in shielding and metallic parts of the facility (accelerator and ancillary structures). As collected along this work, results achieved in several task characterizing the response of monitors and carried out experimental measurements in proton centres, show that uncertainty in monitors

and REM-meters response could vary from 3% to 10%, depending on energy of neutrons and orientation of the monitor relative to the source of radiation.
7. In addition to the fixed monitors mentioned, it would be absolutely essential to have and handle portable devices for gamma, neutron and contamination detection, in order to check several equipment and materials liable of being activated during the operation of the facility, as ground water, heating and air conditioned (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 the accelerator room it would be advisable to wear ring dosemeters and active devices (APDs).
9. Considering the distinctive spectrum of the proton centers, 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. Currently there are no devices with a suitable response for all energy ranges, so it is recommended to use complementary monitors, with efficient responses in different ranges.
10. Because of the previous point, neutron field characterization of the facility, both, energy spectra and angle, should be carried out and regularly updated, in order to state specific facility and local correction factors (LCF), using proper devices and wide range equipment as Bonner spheres, slab phantoms or ambient monitors, among others.

These ten recommendations could be summarized in the Ten Commandments of Operational Radiation Protection at CPTC as follows:

1. Select a suitable site and location for facility
2. Design barriers and shielding against neutron and gamma radiation
3. Use Monte Carlo simulations and check with analytical methods (or if you prefer, the opposite)
4. Choose appropriate materials in barriers
5. Review the impact of radiation on environment
6. Anticipate changes in assumptions and future developments
7. Place the right radiation monitor in the right place of the facility
8. Pick suitable personal dosemeters
9. Assume uncertainties but collect as much information as possible (soil, cement, concrete,…)
10. Carry out experimental measurements

As a result of the activities discussed above, some recommendations could be suggested for the next revision of ICRP Publication 127

1. New delivery modes and dose deposition systems under development will change some assumptions of the Publication 127, and could have a huge impact in the radioprotection of proton centers. PMAT could reduce the ambient dose while Proton-FLASH, which involves Pulsed Neutron Fields (PNF) of high intensity and energy, probably will rise the requirements. The impact of these new deliver methods over points as activation in barriers, metallic elements and air, or personal dosimetry, among others, should be also be also carefully considered.
2. Regarding air activation, results achieved using guidelines of Publication 127 underestimate the ^{41}Ar production about three times, while ^{15}O production is overestimated about ten times, when compared with Monte Carlo results. Production of ^{13}N is in good agreement with both methods. The use of constant cross-section in analytical calculations lies behind these deviations.

3. The cooling circuits of the equipment that run through the acceleration rooms and the gantry are susceptible to activation of water. Considering the self-shielding factors of water, and that the dose rate from activation processes will always be comparatively lower than that in metallic components, they are almost negligible. However, there are no recommendations in Publication 127 about water activation in proton centers.
4. Soil characterization and remediation before building and mitigation actions, as isolation, could be recommended in the new update of Publication 127.
5. Experimental measurements would help to achieve more precise assumptions (always in the conservative side). Publication 127 could suggest the use of some neutron devices able of measuring high-energy neutrons and pulsed neutron fields (PNF). Active measurements should be supported with reliable data from passive monitors.

There is a current general trend to reduce the size of proton therapy centers and make them increasingly compact. This strategy seeks on the one hand, to cut down the direct costs of deployment, since the smaller the center is, the lower the price should be. On the other hand, if extremely small proton equipment were achieved, it would be possible to place them in rooms with the same size as conventional radiotherapy (using photons), which would also produce an indirect reduction in the cost of implantation. In this hypothetical limit scenario, a space for conventional radiotherapy with photons could be replaced by a facility with protons [47]. The final goal is to achieve more affordable proton therapy facilities so that if there are more proton centers, proton treatments can reach more patients, since it is estimated that currently only 1% of patients receive proton therapy, when, if they could have access, between 15% and 50% could benefit from these treatments. The reason for this discrepancy is the high capital cost and the size of the proton therapy equipment [48]. Apparently, the main factor impacting in the high cost of the proton centers is the rotating gantry, whose missions are, on the one hand, to support the beamline from the accelerator to the patient, and on the other, to drive the current with the most efficient angle to treat accurately the tumor. The gantry is made up of a large metallic structure weighing several tons, with large size and height of several floors. Consequently, some new developments limit the angle of rotation of the gantry to reduce the size and cost of the proton facilities [49].

Some research based on the follow-up of treatments dispensed in proton therapy centers for ten years, conclude that only certain orientations of the gantry are necessary for most cases. In other words, using a fixed gantry, a stretcher with a more versatile patient positioning system, more efficient immobilization systems, and more precise image guidance systems, smaller and cheaper proton therapy facilities would be possible, thus more proton therapy centers could be built, and more patients could have access to proton treatments [50]. However, even if technological advances in medical treatments and tools, could lead to reduce the size of proton therapy centers as conventional radiotherapy rooms, the operational radiological protection of these super-compact proton facilities would be an even more demanding challenge.

Currently, compact proton therapy centers are in full expansion throughout the world, therefore the study of the impact of these new developments on operational radiation protection, proposed in this work, is an important task that must be considered. Although the study of radiological protection in multi-room centers has been widely studied elsewhere, however, compact centers have specific features that pose a challenge in radiation protection, therefore the present work makes different contributions to the body of knowledge in these compact facilities. Considering the new methods of application of dose in development (flash-therapy with protons, for example), future works must be carried out to study their impact on operational radiation protection.

Considering the constant evolution in many aspects of proton therapy, international recommendations, as ICRP Publication 127, should be periodically updated, and some suggestions have been pointed in this work.

In short, the results reached in the activities of the project, show that new CPTC have a relevant impact on the operational radiological protection and must be shaped to the challenges of these facilities. Finally, the development of more efficient radiation protection measures could, significantly, reduce the thickness of the barriers, lowering the cost and size required to implement a proton therapy center, and in this way, the access to proton therapy could be easier for more countries and patients. Therefore, the contributions of radiological protection to achieve affordable proton centers and more patients benefit from these highly effective treatments should not be overlooked.

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