https://doi.org/10.17163/abyaups.49.375

Study of air activation in the first public proton therapy center planned in Spain at the Marques de Valdecilla University Hospital (HUMV) in Santander

Cristina Ratero Talavera
Universidad Politécnica de Madrid, España
Orcid: https://orcid.org/0009-0000-9438-0478

Lenin E. Cevallos-Robalino
Grupo de Investigación en Micro-Nanotecnología y Energía Nuclear (NANOTECH),
Universidad Politécnica Salesiana, Ecuador
Orcid: https://orcid.org/0000-0001-9970-5286

Nuria García-Herranz
Universidad Politécnica de Madrid, España
Orcid: https://orcid.org/0000-0002-0760-2974

Gonzalo F. García-Fernández
Universidad Politécnica de Madrid, España
Orcid: https://orcid.org/0000-0003-1809-6058

Introduction

The main advantage of using proton beams in radiotherapy lies in the physical characteristic of protons, linked with the dose distribution pattern defined by the so-called Bragg plot. Considering these benefits, there has been a significant expansion of centers worldwide in recent years, with currently 108 proton therapy centers in operation, 33 under construction, and 38 in the planning stage (PTCOG, 2022).

Based on International Basic Safety Standards and Regulatory Principles (IAEA, 2020), main radiological risks in proton centers have been widely stated and summarized (Yonekura et al., 2016):

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.

As other radioactive facilities where neutrons are presents, in proton therapy centers there is activation of air inside the bunker, mainly in the accelerator room, and minor, in the treatment rooms, being negligible in other spaces. The main source of air activation are the fields of secondary neutrons yielded by the beam of primary protons beam, and additionally, direct reactions of protons (IAEA, 2020).

Consequently, the main goal of this work was the study and evaluation of inhalation dose due to radioisotopes generated by air activation during irradiation in proton therapy centers. The study was carried in the proton center planned at Marques de Valdecilla University Hospital (*HUMV*), currently under develop in the city of Santander (Consejeria de Sanidad del Gobierno de Cantabria, 2022). This facility will be the first public proton therapy center in Spain. The work has been developed through three main activities:

- Development of a methodology to get inputs for Monte Carlo Codes, from CAD (Navarro Hernández, 2023).
- Application to the proton therapy center with a compact isocyclotron similar to that planned at *HUMV*, developing its model in Monte Carlo code PHITS (Sato et al., 2018).
- Calculation of neutron activation of the air in the center, by using the code PHITS.

This work is framed into the project *Contributions to operational radiation protection and neutron dosimetry in compact proton therapy centers (CPTC)*, focused on assessing the operational radiation protection of compact proton facilities.

Material and Methods

Compact proton therapy center (CPTC) developed in the work

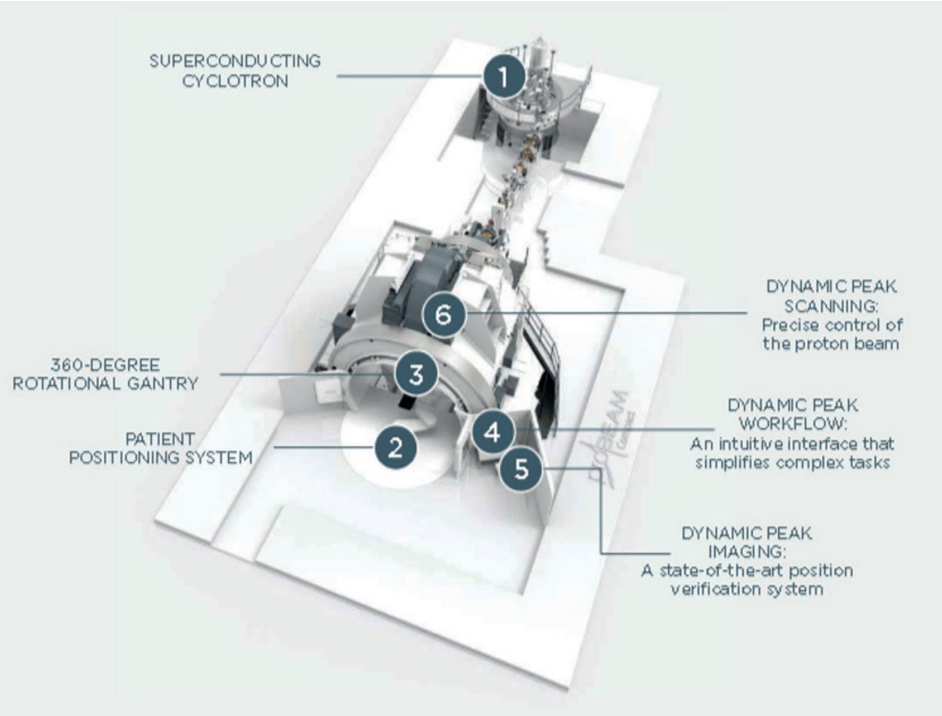
Currently there are two proton centers operating in Spain, both private. The first one, working from December 2019, has a cyclotron accelerator with extraction energy at 230 MeV and a footprint close to 360 m^2. The second one, working from May 2020, has a synchrotron accelerator, with extraction energy adjustable between 70 and 230 MeV and a footprint near 800 m^2 (García-Fernández et al., 2019).

The CPTC considered in this work are the standard version of the first public center planned in Spain at HUMV, in Santander, at the north of Spain. In July 2022, the award of the public tender for the technology of the center was announced (Boletin Oficial de Cantabria, 2020), initially a compact system with a single gantry, and a superconducting isocyclotron-type accelerator, ProBeam360® system, from American firm Varian (Varian, 2023).

In this case, the protons are accelerated through a superconducting isocyclotron, with fixed output energies up to 230 MeV, so it is also necessary to have an energy selection system ESS (Energy Selection System) at the output of the accelerator. The roughly dimensions of a standard center of these characteristics are 17 m wide and 32 m long, therefore the footprint is approximate 544 m^2, and the height is around 14 m in the area of the rotating gantry (Varian, 2023).

HUMV facility is scheduled to start operating in 2025, after two years of construction and testing. The 3D geometry of a proton therapy center similar to the one planned for the HUMV is shown in the following Figure 1.

Figure 1
Main elements of CPTC with isocyclotron at HUMV, from (Varian, 2023)

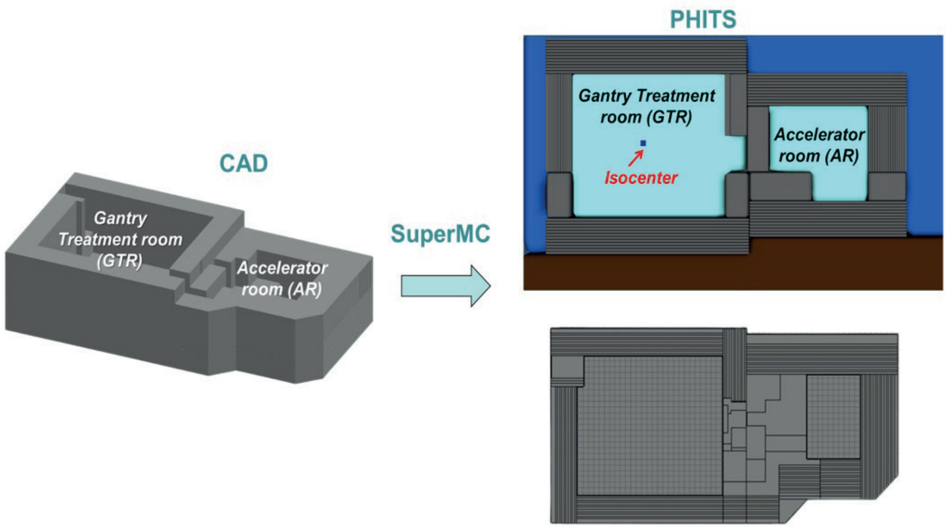


Its main elements are: 1) isochronous superconducting cyclotron-type accelerator, 2) patient positioning system, 3) 360º rotating gantry, 4) and 5) auxiliary systems for patient positioning and treatment verification, and 6) control system of the proton line.

Monte Carlo codes and settings

Facility design, equipment, and materials. SuperMC is a CAD-based automatic geometry and physics modeling software with high efficiency and precision that has been used to convert CAD files into PHITS files (OECD-NEA, 2019). The software transforms geometry files in .sat format, into .txt files, as shown in Figure 2, with cells and surfaces required in the input model, and additionally, the definition of materials, compatible with PHITS.

Figure 2
Conversion process for CAD to PHITS with SuperMC



PHITS 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 Monte Carlo codes (Sato et al., 2018), and using the general nuclear data libraries of PHITS, JENDL-4.0 (Shibata et al., 2011).

Six different simulations were performed using the output file from SuperMC, corresponding to the simulation of different energies of the proton beam. These models were created using the output file from SuperMC as the input file, and the geometry was completed by manually including the cell definition for the ground, external air, internal air, and the air cube in which air activation will be measured. The air cube was placed 1m away from the phantom in x, y and z direction, so the air activation has been measured in the treatment room. It has been modeled that the proton beam directly impacts the phantom, which is not physically possible in the actual installation, but it has no impact on the calculation of air activation, allowing the simplification of the model.

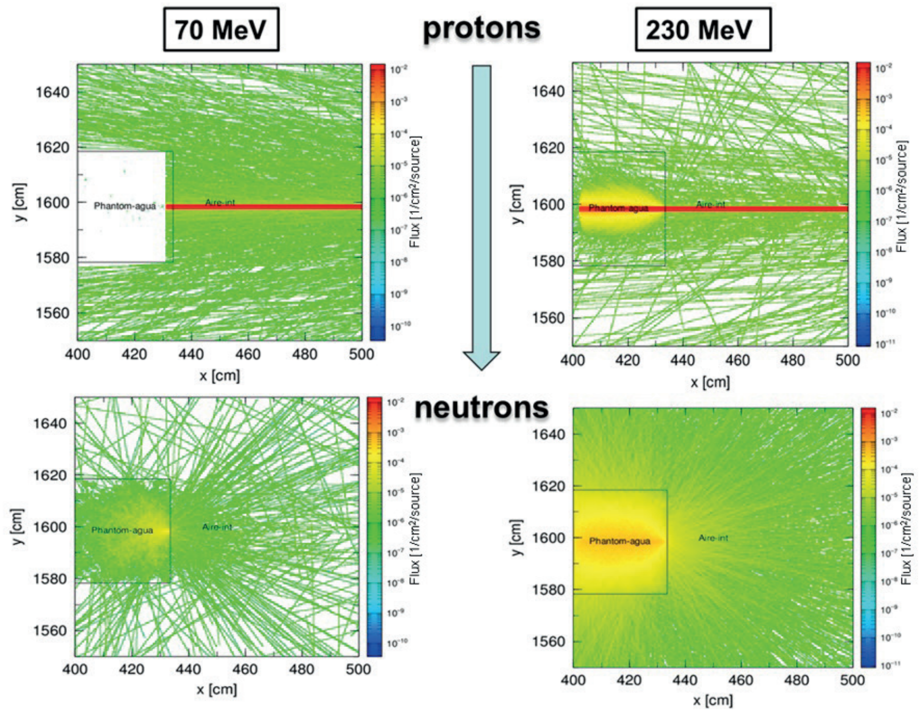
Data of *workload* at the *isocenter* are shown in Table 1.

Table 1
Workload of CPTC considered in this work

Energy (MeV)	Workload at *isocenter* (nA·h·year^{-1})	Intensity (nA)
70	21.12	2.41E-03
86	25.29	2.89E-03
116	29.55	3.37E-03
160	38.01	4.34E-03
200	46.44	5.30E-03
230	50.67	5.78E-03

Figure 3 shows the interaction of the proton beam with the water *phantom* placed at *isocenter*, and the neutron generation, at 70 MeV and 230 MeV, respectively. Protons, and mainly neutrons, are responsible for the activation of the air.

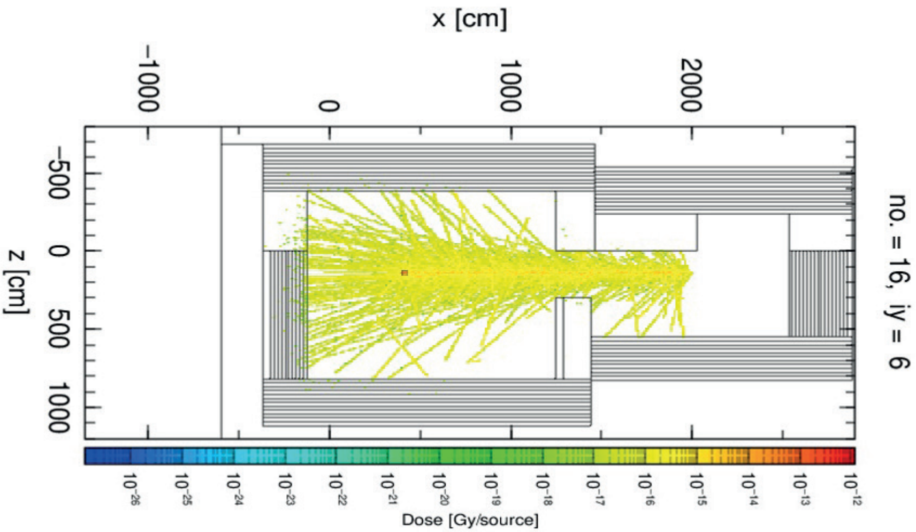
Figure 3
Proton interactions and neutron yielded in the water phantom



As a consequence of those interactions, fields of stray neutron radiation are yielded across the air of the facility, as collected in the next Figure 4.

Figure 4

Main features of CPTC with synchrocyclotron (SC)



The irradiation conditions considered were continuous irradiation for 1 hour, calculating the activity of the isotopes at the end of the irradiation. This moment represents the A_{sat} (saturation activity), which is the balance between produced and consumed isotopes. It corresponds to the point when the inhaled dose reaches its highest peak, representing the worst-case scenario.

Once the saturation activity for each isotope at different energies and the total contribution of the isotope (sum of the activities from all contributing energies) have been determined, the compromised dose factor e50 and a recommended breathing rate of $R = 1.2\ m^3 \cdot h^{-1}$ are applied. The daily dose is calculated as the product of these three values, as shown in Equation 1):

$$\text{Dose}\left(\frac{\mu Sv}{h}\right) = A_{sat}\left(\frac{Bq}{m^3}\right) \cdot e_{50}\left(\frac{Sv}{Bq}\right) \cdot R\left(\frac{m^3}{h}\right) \cdot 10^6 \qquad \text{(Eq. 1)}$$

After determining the relevant hourly doses, the calculations were redone considering ventilation of the room for two cases: a) $r_1 = 6$ air renovations per hour (rph) and b) $r_2 = 10$ rph. For this purpose, a ventilation coefficient (VF) was applied to the saturation activity, calculated as:

$$VF = \frac{\lambda}{\lambda + r} \qquad (Eq. 2)$$

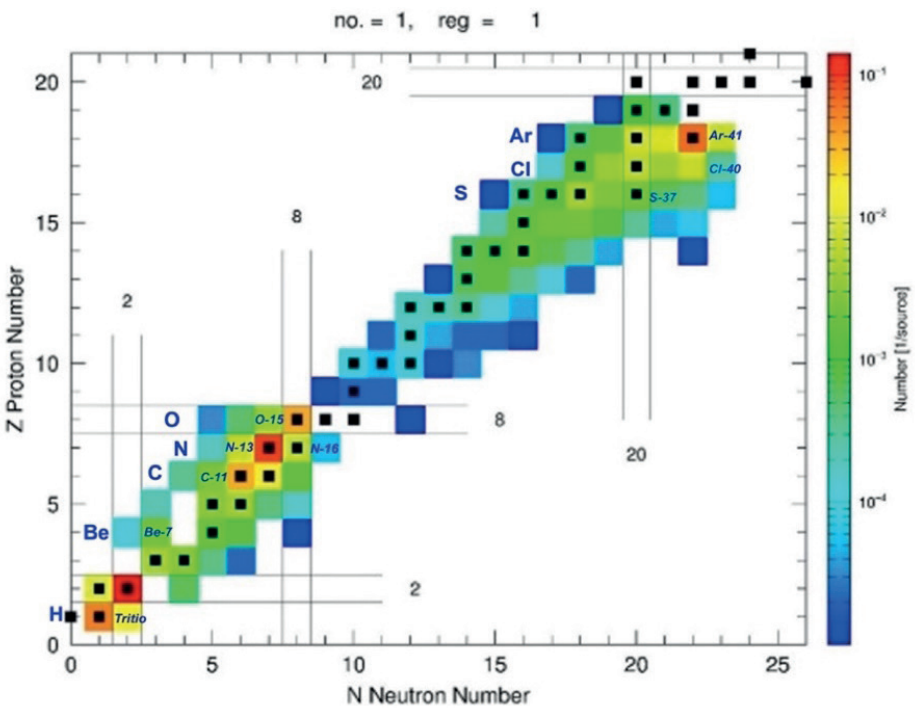
where $T_{1/2}$ is the half-life, λ is the decay constant, and r is the number of air changes per hour.

Results

Radioisotopes yielded in air by neutrons and protons

The main isotopes yielded in air of the gantry treatment room of the HUMV proton therapy center, during irradiation (beam-on), calculated with PHITS, are shown in Figure 5.

Figure 5
Radioisotopes yielded in air by proton and neutron interactions

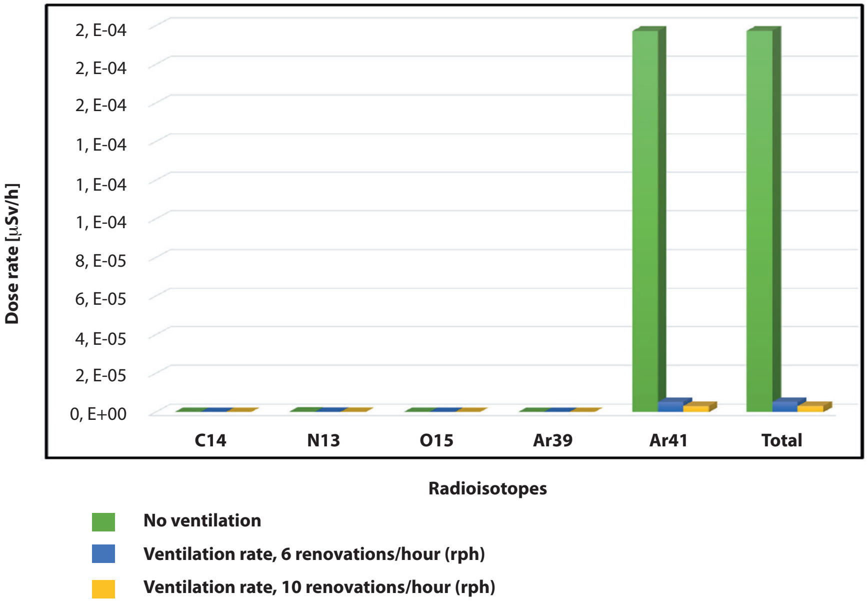


The inventory agrees with the main radionuclides found in experimental measurements in centers of proton therapy and radiopharmaceutical production facilities with cyclotrons, such as N-13, N-16, C-11, S-37, Cl-40 and Ar-41 (Herault, 2018), along with H-3, Be-7, O-15, reported in other works (Infantino, 2015).

Doses from main radioisotopes generated

In Figure 6, the emitted dose for each isotope is shown. This was reached by summing up the dose contributions from each energy of workload, with the result of the total dose rate by isotope.

Figure 6
Dose rate from main radioisotopes



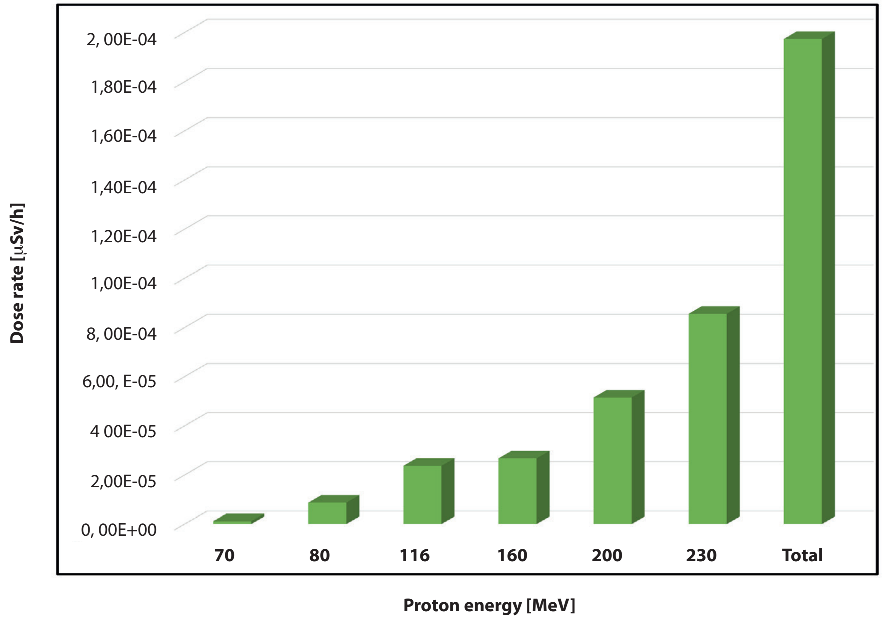
As shown in the Figure 6, in the treatment room, the isotope with the highest saturation activity is Ar-41, followed by O-15, β+ emitter, with half-live of 2.05 minutes, so their contribution to the saturation activity and annual dose will be practically insignificant. In summary, Ar-41, $T_{1/2}$=1.82 hours, is the isotope with the greatest contribution to the effective dose.

The most relevant radioisotope in terms of dose is Ar-41, which represents 99.92 % of total contribution to the inhaled dose. Isotopes have committed dose factors, in Sv/Bq, which differ in some cases by several orders of magnitude, as will be seen later, so the isotope that provides the highest dose will be the one whose saturation activity, multiplied by the dose coefficient is, overall, higher.

Production of Ar-41 based on proton energy

Finally, the contribution from Ar-41 to the dose rate was evaluated based on the energy of the primary protons, and shown in Figure 7.

Figure 7
Generation of Ar-41 based on energy of proton beam



High-energy protons, from 200 MeV to 230 MeV, are the main contributors to the generation of Ar-41, roughly a 70 %, while at medium energies, 116 MeV to 160 MeV) the contribution is nearly 12 %. Table 2 shows the calculated values for emitted dose rate by Ar-41 in the treatment room, in [μSv/h], considering the three scenarios described above.

Table 2
Dose rate by Ar-41 for the three scenarios

	No ventilation	Ventilation rate, r=6 rph	Ventilation rate, r=10 rph
70 MeV	1,14E-06	3,07E-08	1,86E-08
86 MeV	8,74E-06	2,34E-07	1,42E-07
116 MeV	2,37E-05	6,36E-07	3,86E-07
160 MeV	2,67E-05	7,17E-07	4,35E-07
200 MeV	5,15E-05	1,38E-06	8,38E-07
230 MeV	8,56E-05	2,30E-06	1,39E-06
Total	1,97E-04	5,29E-06	3,21E-06

Based on the obtained doses for Ar-41 in the three considered scenarios, it is evident that implementing ventilation measures drastically reduces the emitted dose, decreasing from a total of 1.97E-04 µSv/hour to 5.29E-06 for a ventilation rate of 6 air changes per hour, representing a 97,2 % reduction in dose. With 10 air changes per hour, a reduction of 98.4 % in dose emission is achieved compared to the scenario without ventilation.

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 for patients, medical staff, exposed workers, and the general public.

1. A methodology has been developed to achieve inputs from Monte Carlo Codes, PHITS, from the information in CAD and materials.
2. The inhaled dose is drastically reduced with a correct ventilation, -97.2 % with 6 rph, and -98.37 % with 10 rph, therefore, with the minimum renewal rate (6 rph) it would be enough to efficiently mitigate the dose by activation from air.
3. Qualitatively, ventilation should be maximum at the post-irradiation moment, thus reducing exposure to a minimum.

Although as shown, air activation is not a problem under current operating conditions, there are certain strategies and measures that could reduce exposure, with virtually no cost.

4. Ventilation system: Decentralized ventilation circuits are recommended depending on the installation area.
5. Air flow: System in depression, sucking from the accelerator area, never outwards or towards the isocenter area. Control air renewals independently in each zone:
6. Cyclotron area (AR), 10 renewals/hour, permanently
7. Gantry of the treatment area (GTR) 10 renewals/hour. A recommendable option would be to completely renew the air just before starting the treatment, and just after irradiation.
8. Gantry technical part (gantry pitch), 6 renewals/hour.
9. Control of the pressure with the aim of avoiding a flow of air from the inside to the outside of the bunker, with continuous reading and checking of the pressures.

References

Consejería de Sanidad del Gobierno de Cantabria. (2022). *Resolución de adjudicación del contrato de suministro de un equipo de protonterapia para el Hospital Universitario Marqués de Valdecilla (HUMV) PA SCS 2022/3*.

García-Fernández, G. F., Gallego, E., & Núñez, L. (2019). Los nuevos centros de protonterapia en España. *Radioprotección, Publication SEPR*, 94, 19-28.

Herault, J., & Carnicer, A. (2018). Radiation protection in protontherapy (Nice CALT-IMPT experience). *First International course in protontherapy*, Institute Curie, Paris. Oral presentation.

IAEA. (2020). International Atomic Energy Agency. *Regulatory control of the safety of ion radiotherapy facilities*. IAEA-TECDOC-1891. IAEA, Vienna, 2020.

Infantino, A. (2015). *Advanced aspects of radiation protection in the use of particle accelerators in the medical field*. TD. Universitá Degli Studi di Bologna.

Navarro Hernández, D. (2023). *Desarrollo del modelo de un centro de protonterapia con sincrotrón compacto para estudios de protección radiológica con métodos de Monte Carlo*. TFM, ETSII-UPM.

PTCOG. Proton Therapy Facilities. (2022). Homepage of Particle Therapy Co-Operative Group. https://www.ptcog.ch.

Sato, T, Iwamoto, Y., Hashimoto, S., Ogawa, T., Furuta, T., Abe, S., Kai, T.,Tsai, P. Matsuda, N., Iwase, H., Shigyo, N., Sihver, L. & Niita, K. (2018). Features of Particle and Heavy Ion Tr,ansport Code System PHITS Version 3.02. *J. Nucl. Sci. Technol*., *55*, 684-690. https://n9.cl/jwgnc/

Shibata, K., Iwamoto, O., Nakagawa, T., Iwamoto, N., Ichihara, A., Kunieda, S., Chiba, S., Kazuyoshi Furutuka, K., Otuka, N., Ohsawa, T., Murata, T., Matsunobu, H. Zukeran, A., Kamada, S., & Katakura, J. (2011). JENDL-4.0: A *Journal of Nuclear Science and Technology*, *48*(1), 1-30. https://n9.cl/4ld18/

SuperMC (2023). https://n9.cl/4ytzq/

Varian. (2023). *Proton Therapy*. https://n9.cl/9jrmw/

Yonekura Y., Tsujii H., Hopewell J. W., Ortiz López P., Cosset J. M., Paganetti H., Montelius A., Schardt D., Jones B., & Nakamura T. (2016). Radiological protection in ion beam radiotherapy: practical guidance for clinical use of new technology. *Ann. ICRP; 45 (1_suppl):* 138-147. https://n9.cl/2wpuy/

Acknowledgements

Author Cristina Ratero Talavera thanks the Federico Goded Nuclear Safety Chair, CSN/UPM, for granting a grant to carry out the course on Radiological Protection in Proton Therapy Facilities.