JURNAL KEDOKTERAN DIPONEGORO
(*DIPONEGORO MEDICAL JOURNAL*)
Online : http://ejournal3.undip.ac.id/index.php/medico
E-ISSN : 2540-8844
DOI: 10.14710/dmj.v12i3.38660
JKD (DMJ), Volume 12, Number 3, May 2023 : 157-166

MONTE CARLO NEUTRON DOSE MEASUREMENT IN PROTON THERAPY FOR HEALTHCARE WORKER RADIATION SAFETY

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ABSTRACT
Background: Proton therapy is an innovative and highly advanced external radiation therapy modality for cancer treatment that uses positively charged atomic particles. The usage of proton therapy facilities in Asia has been increasing and will be followed by Indonesia in the short-coming years. In line with its significant benefits, the application of proton therapy also requires radiation protection awareness due to its higher energy used by protons produces scattered photon and neutron radiation in proton interactions. Therefore, optimal verification is needed in the commissioning process for designing proton therapy shielding bunkers. **Objective:** This research aims to evaluate the effect of two layers of concrete density simulation on proton shielding performance on the treatment control room (TCR) and the compact proton therapy center (CPTC) door. **Method:** The proton therapy bunker modelled for this simulation uses Particle and Heavy Ion Transport code System (PHITS) software. The model consists of a synchrocyclotron accelerator room and an examination room with standard configurations, wall thicknesses, and modelling areas under compact proton therapy standards. The analysis wants to determine the neutron exposure dose values, the neutrons equivalent dose H*(10), in the TCR and CPTC doors based on the selected 2.3 g/cm^3 and 4.8 g/cm^3 composite concrete density and wall thickness. The geometry, radiation source, and concrete composition of the wall are simulated based on a realistic proton therapy bunker model. **Result:** At the designated TCR and CPTC door, the simulated average measured H*(10) doses were 32 µSv/year and 99 µSv/year, respectively. The results indicate that the equivalent dose H*(10) values were below the implemented dose limit for healthcare workers' radiation safety in Indonesia (20 mSv/year). **Conclusion:** This study showed that the designated bunker's concrete density could reduce the equivalent dose H*(10) below the radiation safety limit for healthcare workers in Indonesia.
Keywords: *Proton Therapy, PHITS, Monte Carlo, Neutron*

INTRODUCTION

Proton therapy is a branch of radiation therapy that uses proton beams as its radiation source. The modality typically operates in the energy range between 70 to 230 Mega electron-volts (MeV). Proton therapy has the advantage of treating several tumors with unique proton depth dose characteristics. Therefore, it can significantly reduce the dose at the surrounding normal tissue volumes relative to the target volume. This advantage enables greater normal tissue sparing and potentially enhances local control and survival while reducing toxicity and improving quality of life[1]. The number of proton therapy facilities has increased significantly in the last decade. In 2008, there were about twenty proton therapy facilities worldwide, and more than one hundred facilities have been built nowadays[2]. As proton therapy centers continue to grow worldwide, the current model of proton therapy centers is also evolving. The current trend is to build compact proton therapy centers (CPTC) as a development of previously multiple-room proton therapy centers (MPTC) in the 1990s[3]. Compact Proton Therapy Centers (CPTCs) typically feature a standard equipped with one or two treatment rooms and advanced technology to reduce the size of the facility and treatment rooms[4].

In proton therapy machines, the protons produced for clinical use undergo several interactions with the modality materials, such as the accelerator and the energy-selection system. Moreover, the proton also interacts with the patient. The interaction of protons with these materials results in complex scattered radiation. Under the spallation process, radiation activation is generated, i.e. the interaction of protons with the patient produces neutron radiation, usually called thermal-neutron. Meanwhile, the proton interaction with the modality mechanical elements produces neutron radiation, known as fast-neutron[3]. In general, the secondary radiation of proton therapy components

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creates medical effects on tissue targets, as reported by a study[5].

Summarized by previous study[6], the shielding calculation of proton therapy facilities has three main methods; analytical, monte carlo, and hybrid. In its practice, each method involves several assumptions. In the analytical model, the dose at the target location is assumed to be produced by a point source[7,8,9]. Meanwhile, the Monte Carlo method evaluates and tracks primary and secondary particles' interactions with materials by considering the particle database information and the material properties[10,11]. When analytical method data is obtained from the Monte Carlo method, the combination is called the hybrid method[12].

The safety of proton therapy utilization for healthcare workers is one of the primary concerns in proton therapy installation. Commonly, at the facility, the workers work in the Treatment Control Room (TCR) and near the CPTC door. Therefore, shielding calculation in these areas should be simulated and calculated before constructing the proton therapy bunker. Moreover, the calculation must be verified[13] at the commissioning stage by comparing its results to experimental measurements at the facility using detectors[14]. In order to evaluate proton therapy bunker performance, this study aims to assess and estimate the neutron dose outside the shielding wall in the operator room and CPCT door by calculating the ambient equivalent dose H*(10). The calculation is done through a stochastic approach using Monte Carlo-based PHITS software by calculating the neutrons' secondary radiation produced from the protons to a water phantom interaction. The shielding material used is a composite of conventional Portland concrete with a 2.3 g/cm^3 density and Nelco concrete with a 4.8 g/cm^3 density.

MATERIAL AND METHODS

The Layout of the Proton Therapy Facility

The CPTC modality discussed in this study consists of three key elements: the accelerator, the beamline system, and the gantry treatment system. The S2C2 cyclotron accelerator is designed to produce and accelerate protons to a fixed energy of 230 MeV. This accelerator is located in a separate room called the accelerator room and has its labyrinth. The beamline system is a proton's transport system from the accelerator to the treatment room and consists of the energy selection system (ESS) and the beam treatment system (BTS). The beamline system uses a patient's dose delivery system through pencil beam scanning (PBS). The gantry treatment system is compact and can rotate up to 220^o. Simultaneous and automatic rotation ability ensures the control of the proton path to the patient table in achieving optimal treatment positions[15].

The main dimensions, especially for the wall width, of the CPTC layout are shown in Figure 1. The usual CPTC model is 28 m × 12.8 m (360 m^2) rectangular for construction and architecture applications. The model is divided into three main rooms: the accelerator room, the gantry treatment room (GTR) with the rotating gantry system, and the labyrinth to the CPTC door (Figure 1b). The TCR is located outside the labyrinth wall, as seen in Figure 1b. The TCR is used to monitor patients undergoing radiation. The CPTC door is located next to the TCR area. Access to the accelerator room must pass through the accelerator labyrinth, which reduces scattered radiation from the accelerator aimed at the GTR room. In the proton therapy facility, the accelerator room, the GTR, and the labyrinth have A height of 3.8 m, 7.7 m, and 3 m, respectively (Figure 1a). The GTR room must have a greater height to allow the mechanical gantry structure to rotate around the isocenter, which is mounted on the partition wall of the accelerator room. The isocenter is the intersection point between the nozzle proton path and the gantry rotation axis.

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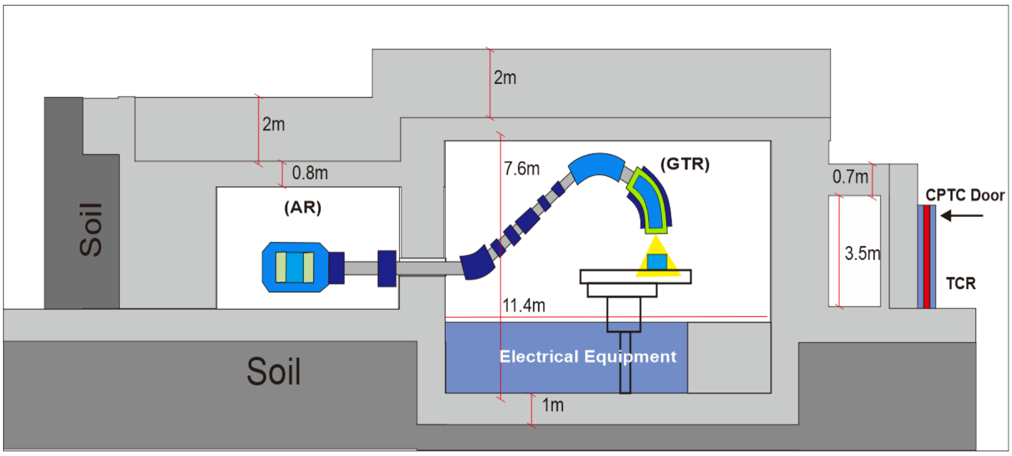
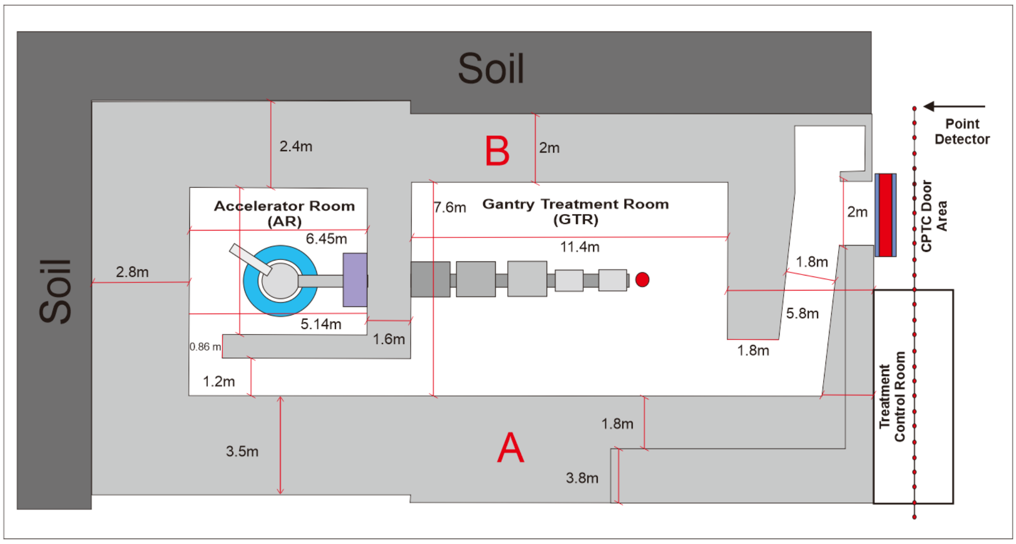


(a)



(b)

Figure 1. The side view (a) of the compact proton therapy center (CPTC) layout for a 0° radiation angle from the source to the patient's bed. The position of the TCR and the CPTC door is determined from the layout's top view (b).

The Proton Therapy Shielding Specification

In the proton therapy application, the materials used to shield the walls and roof of the bunker facility influence the effectiveness of the neutron scatter radiation reduction outside the bunker. In its practice, the concrete material used on the walls and roof of the bunker greatly affects the quality of radiation scattering attenuation outside the walls. The concrete commonly used in proton therapy facilities is standard concrete with a 2.3 g/cm^3 density [16]. On its use, the atomic composition of the cement, water, and final concrete characteristics directly affect the quality of the protection against neutron radiation[17]. This study uses a 2.3 g/cm^3 standard concrete containing approximately 10% water after mixing and a higher proportion of oxygen to compensate for its lower hydrogen content. Thus, the concrete has a macroscopic cross-section of fast neutrons attenuating around 85% of that of water. Moreover, when processed, the concrete's higher density and

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effective atomic number can produce a higher gamma radiation attenuation capacity than water[18].

In this study, the wall facing the Treatment Control Room (TCR) is constructed using two layers of concrete with different densities. The inner layer is made of concrete with a 2.3 g/cm^3 density, while the outer layer is made of concrete with a 4.8 g/cm density. Most of the scattered neutrons produced by the system are low-energy neutrons, and the most effective way to slow them down to thermal energy is to use a high hydrogen content material, followed by boron, to capture these slow neutrons. This study's door material composition consists of stopping high-energy gamma radiation due to neutron capture. One layer of Boron-loaded High-Density Polyethylene (HDPE) with at least 5% boron by mass, assuming a thickness of 50 cm of B-loaded HDPE. The shielding material components, phantom, and CPTC door are summarized in Table 1.

Table 1. Feature of Material in PHITS, adapted from[16,19]

Material	Composition (Atomic Fraction)	Density (g/cm^3)
Air (vaults)	75.53% N, 23.18% O, 1.28 Ar, 0.01% C	1.2×10^{-3}
Water	67% H, 33% O	1
Natural soil (Earth)	55% O, 23.8% Si, 11.10% Al, 4.20% Mg, 3.5% Fe, 1.7% H, 0.71% Ca	1.8
Air (void in proton line)	78% N, 22% O	1.6×10^{-11}
Portland concrete	53% O, 33.7% Si, 4.4% Ca, 3.4% Al, 1.6% Na, 1.4% Fe, 1.3% K, 1% H, 0.2% Mg, 0.1% C	2.3
Nelco Concrete	0,5% H, 10,4% O, 0,2% Mg, 0,4% Al, 3,4% Si, 19,7% P, 4,2% Ca, 61,2% Fe	4.8
Polyethylene, Borated	12% H, 10% B, 77% C	1
Iron	100% Fe56	7.87
Aluminium	100% Al27	2.7

Modeling CPTC facilities and neutron sources with PHITS

The PHITS program is a Monte Carlo particle transport program developed jointly by the Japan Atomic Energy Agency and other institutions[20,21]. PHITS models interactions between neutrons, protons, photons, electrons, mesons, and heavily charged particles; therefore, it is extensively used in proton therapy studies[22,23].

In this study, PHITS was used to calculate three things; firstly, it calculated the neutron fluence, using the [T-cross] card, that passed the shielding; secondly, the neutron fluence from the selected phantom; and lastly, it calculated, around the treatment room using the [T-point] card, the ambient equivalent dose rate at 30 cm. In the PHITS program, the "multiplier" parameter combines the [T-point] card with the corresponding [Multiplier] card and converts the calculation results into the ambient equivalent dose rate H*(10), which is the depth of 10 mm from the body's surface, indicates the equivalent dose received by the whole body. The calculation results in the PHITS output file are normalized per source particle, representing the contribution of each proton to the total ambient equivalent dose rate and neutron fluence.

The shielding verification was done by estimating the ambient equivalent dose, H*(10), at various exciting locations behind the enclosure. Nuclear data were taken from La150n[24], TENDL2017 (neutron, proton, and gamma)[25], and JEFF-3.3. (neutron)[26]. In the PHITS program simulation process, the error value must be below 3% to achieve statistical uncertainty, with the number of proton histories performed in the simulation being 10^9. Following International Commission on Radiological Protection (ICRP) and International Committee for Radiological Units (ICRU), the conversion function h(E), whose value depends on neutron energy, considers 20 neutron energy groups in the neutron fluence calculus from 10^{-9} MeV to 230 MeV[10].

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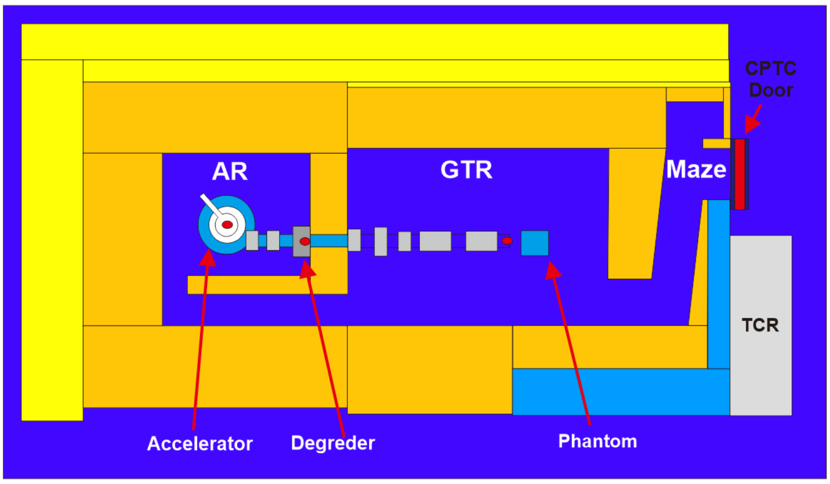
Regarding neutron interaction with hydrogen, the thermal treatment S(α,β) is considered in PHITS because this model is more accurate than the default free-gas model[27]. Several publications are used to evaluate this study's hypothesis, assumptions, and data facility[10,16,28]. The shielding validation, using the PHITS code[27], is conducted in three main stages as previously done in a multi-room proton center[29] by MPTC. The first step is defining the geometry, equipment, and potential radiation sources, then modelling the source (intensity and energy) through condensation. Afterwards, shielding verification is conducted by estimating the equivalent environmental dose, H*(10), at desired points of interest (POI). The critical point of this study is to measure the dose rate outside the CPTC shielding walls, particularly in the TCR area and CPTC door, which are essential spaces in proton therapy facilities where radiation workers are present. This study focused on evaluating and verifying the neutron radiation dose rate passing through the shielding walls of the TCR area, consisting of two layers of concrete with different densities and the CPTC door coated with boron.

In assessing PTC shielding with complex geometry, the amount of detail required in the simulation is tremendous and takes high computational time to achieve statistical convergence. Therefore, PHITS uses variation reduction techniques such as the cutoff, population control, modified sample, and partially deterministic methods to reduce computation time and avoid bias in the results. Since a vast factor usually attenuates the neutrons produced in the room, the probability of detecting neutron tracks in the counting cell located outside the shielding is very low. Therefore, appropriate weighting factors are applied to the tracked particles to reduce computation time and follow neutrons individually with statistical significance.

The geometry, design, and drawings were converted into the PHITS input file [30]. PHITS calculations assume that all bunker rooms are air-filled, whose composition and properties are generally shown in Table 1. In this study, the model and materials in the bunker were tested in the PHITS program to verify and ensure that the shielding in the CPTC followed the desired geometry. The material chosen for this bunker is Portland concrete with a density of 2.3 g/cm^3, shown in orange, and concrete with a density of 4.8 g/cm^3, shown in blue in Figure 2a, and the primary radiation source is directed at the patient (or phantom in this case). In this study, it is assumed that proton loss occurs at the center of the source, namely at the phantom or patient site, and the proton beam is assumed to experience a loss of 33.08%[10].



(a)

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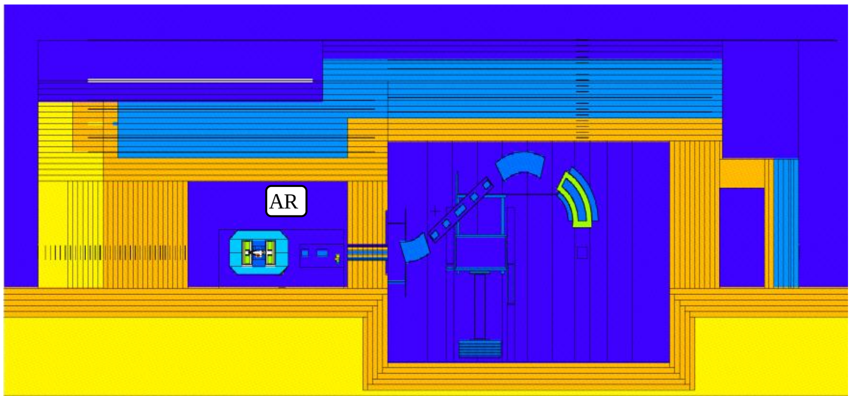

(b)

Figure 2. (a) Side view of CPTC bunker model in PHITS program, (b) Top view of CPTC bunker model in PHITS program.

Facility workload

The workload is estimated according to published data for this CPTC, in nA·h per year at each energy, at the time of accelerator operation[16], assuming a conservative approach of 16-hour workdays in two 8-hour shifts, six workdays per week, and fifty weeks per year, 450 patients/year, 17,000 sessions, with 2 Gy/session, taking into clinical account data on patient numbers and typical treatment plans[31]. Occupancy factors were obtained from international recommendations by selecting the most conservative option[32]. This study used an occupancy factor of 0.20 around the perimeter walls, while at the TCR, the occupancy factor is assumed to be 1 for the room typically only accessible to exposed workers. Regarding beam orientation, the final assumption is that when oriented on the floor, the beam works with a workload of 25%. Meanwhile, when oriented towards the ceiling and the wall close to the TCR, the workload is 25% and 50 %, respectively. However, only ceiling and wall close to the TCR orientations are considered in the calculation, as there are typically unoccupied natural fields below the GTR floor[10].

RESULTS

In the equivalent environmental dose, H*(10) of the neutron dose is calculated to assess and verify the effectiveness of the bunker. The consideration is that the photon dose is much lower[33] and irrelevant during the verification phase. Similarly, the dose caused by induced activation is not included in the results during this commissioning phase. The simulation results showed that the dose values obtained from the 28 detectors from the TCR room to the CPTC door area were not uniform, as seen in Figure 3. Figure 3(a) shows the graph of the equivalent dose variation from each detector point read from the PHITS simulation results, which are divided into two areas: the TCR area with 17 measurement points and the CPTC door area with 11 measurement points. Meanwhile, Figure 3(b) is a model of the PHITS program that explains the results of Figure 3(a).

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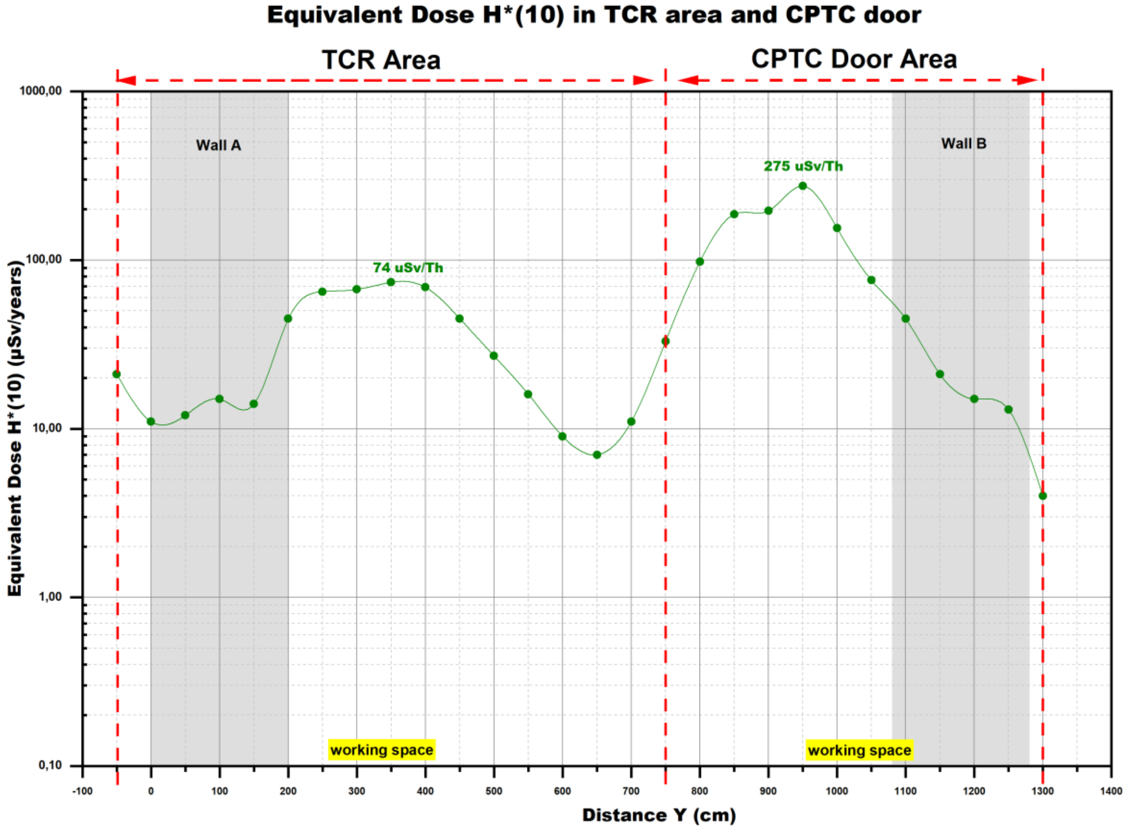
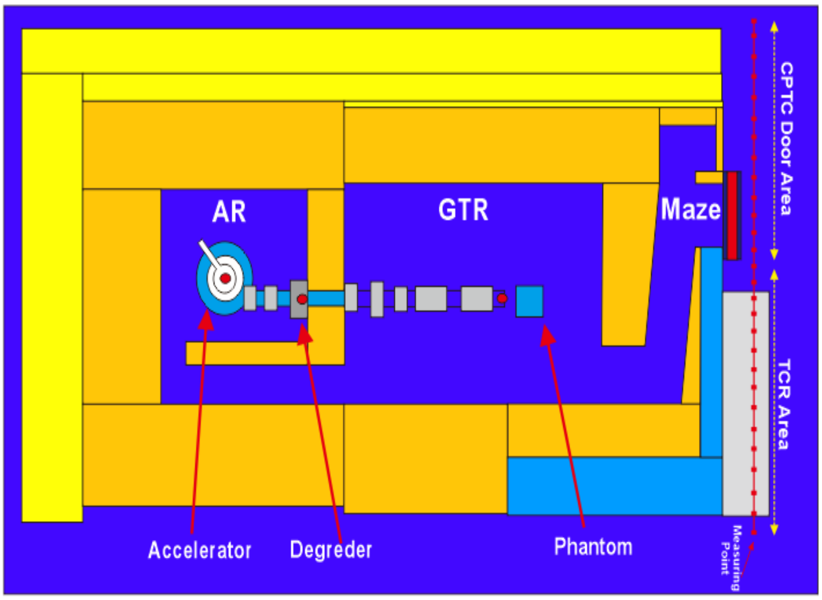


(a)



(b)

Figure 3: (a) Equivalent Dose H*(10), in TCR and CPTC Door Area acquired from the PHITS simulation design (b).

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DISCUSSION

Based on the simulation graph obtained in Figure 3 (a), it is known that in the TCR area with a width of approximately 750 cm, there are 17 measurement points. The lowest dose obtained in the TCR area is 7 µSv/year, and the highest in the TCR area is 74 µSv/year. The average dose in the TCR area is 32 µSv/year. On the other hand, in the CPTC door area with a width of approximately 550 cm, there are 11 measurement points. From these measurement points, the lowest dose in the TCR area is 4 µSv/year, and the highest dose in the CPTC door area is 275 µSv/year. The average dose in the CPTC door area is 99 µSv/year. It can be seen that the average equivalent doses in the two areas are significantly different, with the average dose in the TCR area being almost one-third of the dose in the CPTC door area. This difference is due to two maze walls and different densities of concrete in the TCR area, significantly reducing the radiation dose originating from the GTR.

On the other hand, the dose in the CPTC door area is higher than in the TCR area because there is only one maze wall inside the door that attenuates the radiation from the GTR. The most significant neutron radiation attenuation in the CPTC door area occurs in the door layer, which uses Boron-loaded High-Density Polyethylene (HDPE) with a thickness of 50 cm. The results showed that the acquired equivalent dose H*(10) values were still below 20 mSv/year, the implemented dose limit for healthcare workers' radiation safety in Indonesia. However, the results must be compared with direct experimental measurements using a neutron survey meter. The comparison was planned when the proton therapy facility is installed in Indonesia soon. Experimental measurements will enable the comparison of different models and simulation calculations developed in this study, as well as the development of a methodology to analyze neutron radiation in CPTCs for evaluating doses for workers and the general public.

CONCLUSION

The simulation of the CPTC bunker using the PHITS program has been conducted in this study. This model encompasses various sources of uncertainty, particularly the composition and density of concrete, core data, and interaction models, which showed that the designated design still follows the implemented dose limit regulation for healthcare workers' radiation safety in Indonesia.

REFERENCES

1. R. Mohan and D. Grosshans, Proton therapy – Present and future, *Adv. Drug Deliv. Rev.*, vol. 109, pp. 26–44, 2017, doi: 10.1016/j.addr.2016.11.006.
2. PTCOG, Particle Therapy Co-Operative Group, 2019.
3. U. Schneider, R. A. Hälg, and T. Lomax, Neutronen in aktiver Protonentherapie: Parametrisierung von Dosis und Äquivalentdosis, *Z. Med. Phys.*, vol. 27, no. 2, pp. 113–123, 2017, doi: 10.1016/j.zemedi.2016.07.001.
4. H. Owen, A. Lomax, and S. Jolly, Current and future accelerator technologies for charged particle therapy, *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 809, pp. 96–104, 2016, doi: 10.1016/j.nima.2015.08.038.
5. S. Agosteo, A. Mereghetti, E. Sagia, and M. Silari, Shielding data for hadron-therapy ion accelerators: Attenuation of secondary radiation in concrete, *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 319, no. 2014, pp. 154–167, 2014, doi: 10.1016/j.nimb.2013.10.015.
6. N. Ipe *et al.*, SHIELDING DESIGN AND RADIATION SAFETY OF CHARGED PARTICLE THERAPY FACILITIES - Report 1, 2010. [Online accessed on May 10, 2023]. Available: http://www.ptcog.ch/archive/Software_and_Docs/Shielding_radiation_protection.pdf
7. F. d'Errico, NCRP Report no. 144 Radiation protection for particle accelerator facilities National Council on Radiation Protection and Measurements Issued 31 December 2003; revised 7 January 2005: NCRP, Bethesda, MD, USA ISBN: 0-929600-77-0, 499 pp, $100 (Hardcover), *Radiat. Prot. Dosimetry*, vol. 113, no. 4, pp. 456–457, 2005, doi: 10.1093/rpd/nch479.
8. IAEA, *Radiological Safety Aspects of the* Operation *of Proton Accelerators, Technical Reports Series no. 283*. 1988.

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(*DIPONEGORO MEDICAL JOURNAL*)
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JKD (DMJ), Volume 12, Number 3, May 2023 : 157-166

9. Y. Makita, T. Nakamura, H. Tsuchidate, and M. Yamazak, Radiation shielding design of a cancer therapy facility using compact proton synchrotron, *J. Nucl. Sci. Technol.*, vol. 41, pp. 18–21, 2004, doi: 10.1080/00223131.2004.10875634.
10. T. Urban and J. Kluson, Shielding calculation for the Proton-Therapy-Center in Prague, Czech Republic, *Radioprotection*, vol. 47, no. 4, pp. 583–597, 2012, doi: 10.1051/radiopro/2012029.
11. M. T. Prusator, S. Ahmad, and Y. Chen, Shielding verification and neutron dose evaluation of the Mevion S250 proton therapy unit, *J. Appl. Clin. Med. Phys.*, vol. 19, no. 2, pp. 305–310, 2018, doi: 10.1002/acm2.12256.
12. S. Avery, C. Ainsley, R. Maughan, and J. Mcdonough, Analytical shielding calculations for a proton therapy facility, *Radiat. Prot. Dosimetry*, vol. 131, no. 2, pp. 167–179, 2008, doi: 10.1093/rpd/ncn136.
13. L. Jägerhofer, E. Feldbaumer, S. Roesler, C. Theis, and H. Vincke, A Shielding Concept for the MedAustron Facility, *EPJ Web Conf.*, vol. 153, pp. 1–5, 2017, doi: 10.1051/epjconf/201715304006.
14. G. F. García-Fernández *et al.*, Monte Carlo characterization and benchmarking of extended range REM meters for its application in shielding and radiation area monitoring in Compact Proton Therapy Centers (CPTC), *Applied Radiation and Isotopes*, vol. 152. pp. 115–126, 2019. doi: 10.1016/j.apradiso.2019.07.001.
15. IBA, *ProteusONE Brochure and Technical* Information. 2019.
16. R. Tesse, A. Dubus, N. Pauly, C. Hernalsteens, W. Kleeven, and F. Stichelbaut, Numerical Simulations to Evaluate and Compare the Performances of Existing and Novel Degrader Materials for Proton Therapy, in *Journal of Physics: Conference Series*, Oct. 2018, vol. 1067, no. 9. doi: 10.1088/1742-6596/1067/9/092001.
17. T. Piotrowski, M. Mazgaj, A. Zak, and J. Skubalski, Importance of atomic composition and moisture content of cement based composites in neutron radiation shielding, in *Procedia Engineering*, 2015, vol. 108, pp. 616–623. doi: 10.1016/j.proeng.2015.06.188.
18. E. Gallego, A. Lorente, and H. R. Vega-Carrillo, Testing of a high-density concrete as neutron shielding material, *Nucl. Technol.*, vol. 168, no. 2, pp. 399–404, 2009, doi: 10.13182/NT09-A9216.
19. R. M. Jr, C. Gesh, R. Pagh, R. Rucker, and R. W. III, Compendium of Material Composition Data for Radiation Transport Modeling, 2011, [Online accessed on May 10, 2023]. Available: www.pnnl.gov/main/publications/external/technical_reports/pnnl-15870rev1.pdf
20. K. Niita, T. Sato, H. Iwase, H. Nose, H. Nakashima, and L. Sihver, PHITS-a particle and heavy ion transport code system, *Radiat. Meas.*, vol. 41, no. 9–10, pp. 1080–1090, 2006, doi: 10.1016/j.radmeas.2006.07.013.
21. T. Sato *et al.*, Features of Particle and Heavy Ion Transport code System (PHITS) version 3.02, *J. Nucl. Sci. Technol.*, vol. 55, no. 6, pp. 684–690, Jun. 2018, doi: 10.1080/00223131.2017.1419890.
22. H. Kumada, T. Nakamura, M. Komeda, and A. Matsumura, Development of a multi-modal Monte-Carlo radiation treatment planning system combined with PHITS, *AIP Conf. Proc.*, vol. 1153, no. 2, pp. 377–387, 2009, doi: 10.1063/1.3204547.
23. Z.-Y. Yang *et al.*, Inter-comparison of Dose Distributions Calculated by FLUKA, GEANT4, MCNP, and PHITS for Proton Therapy.
24. J. L. Conlin, Listing of Available ACE Data Tables (LA-UR-17-20709), 2017.
25. A. J. Koning, D. Rochman, J. C. Sublet, N. Dzysiuk, M. Fleming, and S. van der Marck, TENDL: Complete Nuclear Data Library for Innovative Nuclear Science and Technology, *Nucl. Data Sheets*, vol. 155, pp. 1–55, 2019, doi: 10.1016/j.nds.2019.01.002.
26. NEA, JEFF-3.3 Thermal Scattering Law (TSL) sublibrary, 2018. [Online accessed on May 10, 2023]. Available: https://www.oecd-nea.org/dbdata/jeff/jeff33/index.html
27. F. S. Englbrecht *et al.*, A comprehensive Monte Carlo study of out-of-field secondary neutron spectra in a scanned-beam proton therapy gantry room, *Z. Med. Phys.*, vol. 31, no. 2, pp. 215–228, May 2021, doi: 10.1016/j.zemedi.2021.01.001.

JURNAL KEDOKTERAN DIPONEGORO
(*DIPONEGORO MEDICAL JOURNAL*)
Online : http://ejournal3.undip.ac.id/index.php/medico
E-ISSN : 2540-8844
DOI: 10.14710/dmj.v12i3.38660
JKD (DMJ), Volume 12, Number 3, May 2023 : 157-166

28. T. Vanaudenhove, F. Stichelbaut, A. Dubus, N. Pauly, and V. De Smet, Monte Carlo calculations with MCNPX and GEANT4 for general shielding study-Application to a proton therapy center, *Prog. Nucl. Sci. Technol.*, vol. 4, no. January, pp. 422–426, 2014, doi: 10.15669/pnst.4.422.
29. C. Paper and F. D. Invap, Tests & Benchmarking Methodology for a 230 Mev Proton Accelerator Calculations, no. March, 2016.
30. T. Goorley *et al.*, Initial MCNP6 release overview, *Nucl. Technol.*, vol. 180, no. 3, pp. 298–315, 2012, doi: 10.13182/NT11-135.
31. V. Verma, M. V. Mishra, and M. P. Mehta, *A systematic review of the cost and cost-*effectiveness *studies of proton radiotherapy*, vol. 122, no. 10. 2016. doi: 10.1002/cncr.29882.
32. AEA, No Title, 2006.
33. C. Sunil, Analysis of the radiation shielding of the bunker of a 230 MeV proton cyclotron therapy facility; comparison of analytical and Monte Carlo techniques, *Appl. Radiat. Isot.*, vol. 110, pp. 205–211, 2016, doi: 10.1016/j.apradiso.2016.01.023.