Original Article

Measurement of Ambient Dose Equivalent in Compact Proton Therapy using In-house Neutron Moderator-based Poly Allyl Diglycol Carbonate

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Abstract

Purpose: The high-energy proton produces the unwanted dose contribution from the secondary neutron. The main purpose of this study is to report the validation results of in-house neutron moderator based on poly allyl diglycol carbonate (CR-39) detector, Chulalongkorn University Neutron Moderator (CUMOD) through the ambient dose equivalent, $H^*(10)$ measurement. **Materials and Methods:** The Particle and Heavy Ion Transport code System (PHITS) Monte Carlo code was used to simulate the neutron response function. The CUMOD was calibrated with ^{241}AmBe source calibrator in the range of 100–1000 µSv. The variation of neutron fields was generated employing different proton treatment plans covering most of the clinical scenarios. The ambient dose equivalents, $H^*(10)$, evaluated employing CUMOD were compared to those obtained with WENDI-II dosimeter. **Results:** The linear relationship between CUMOD and WENDI-II responses showed an R^2 value close to 1. The $H^*(10)$ per Gy delivered dose was in the range of 22–105 µSv for a 10 cm × 10 cm field. **Conclusion:** The in-house CUMOD neutron moderator can expand the neutron detection dose range of CR-39 detector for ambient dose equivalent. The advantage of CUMODs is its capability to evaluate $H^*(10)$ in various positions simultaneously.

Keywords: Ambient dose equivalent, compact proton therapy, polyallyl diglycol carbonate, neutron moderator

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Introduction

The compact proton therapy, single rotating gantry, was installed at the Her Royal Highness Princess Maha Chakri Sirindhorn Proton Center, Bangkok, Thailand. The first patient treatment was started in August 2021. In proton therapy, neutron is the main component of the secondary radiations due to proton interaction.[1] Owing to its high radiation weighting factors, they are the main cause of concern for the undue doses to the patient. For this reason, it is important to characterize the out-of-field dose in terms of ambient dose equivalent $H^*(10)$. The $H^*(10)$ can be obtained by multiplying the measured fluence to the fluence-to-ambient dose equivalent conversion coefficients,[2] according to the radiation type and energy. To measure the neutron $H^*(10)$ in proton therapy, the response of the dosimeter to the wide neutron energy range is necessary. Many detectors[3-5] have their own neutron moderator which is designed to expand their detector response function.

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The Wide-Energy Neutron Detector, WENDI-II (Thermo Fisher Scientific, Waltham, MA), has been widely used to measure the $H^*(10)$ both inside and outside the proton treatment room.[6-8] For the evaluation of $H^*(10)$ at various locations, the passive detector could be more effective. The use of poly allyl diglycol carbonate (CR-39) track etched detector in several fields, such as discovering neutron spectrum,[9]

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determining $H^*(10)$ around positron emission tomography cyclotron[10] and 15 MV linear accelerator[11] was the inspiration for employing CR-39. However, the neutron energy response of CR-39 in the range of 200 keV to 14 MeV[12] is a major limitation for our study. Hence, the Chulalongkorn University Neutron Moderator (CUMOD) was created to extend the neutron energy response of CR-39 to 250 MeV and CUMOD was also validated for $H^*(10)$ measurement in proton therapy.

Materials and Methods

This work was performed using the Varian ProBeam Compact Proton Therapy System (Varian Medical System, Palo Alto, CA). It is a compact single-room system with 360° rotating gantry and six-dimensional couch to treat the patients in any direction. The ProBeam enables to deliver for the pencil beam scanning (PBS) technique with energy ranging from 70 to 220 MeV with an expanded field size of up to 30 cm × 40 cm.

In-house neutron moderator-based poly allyl diglycol carbonate detector

To gain reliable readings of the neutron ambient dose equivalent in a wide energy neutron range, the response function of the dosimeter should be close to the fluence-to-dose conversion coefficients. Among our designed dosimeters, the response function was simulated using PHITS[13] Monte Carlo code. The response function of CUMOD was selected and the design is shown in Figure 1. A Cerrobend alloy (Bi, 50%; Pb, 26.7%; Sn, 13.3%; and Cd, 10%) void cylinder of 5 cm inner diameter and 1.5 cm thickness was inserted in a cylinder of 5% Borated Polyethylene (PE) cylinder of 10-cm diameter and 10-cm height. An outer and inner Borated PE is used for moderation and absorption of neutrons of low and medium energies. The 5% Borated PE was selected considering the reduction of the size, without compromising the low-energy neutron's response. The Cerrobend alloy was selected for serving the production of spallation neutrons to increase response for the high energies. The four pieces of CR-39 were equipped inside the CUMOD as presented in the diagram of Figure 1a.

The CR-39 detector (Track Analysis System Ltd, Bristol, UK) is a solid-state nuclear track detector that was selected as the passive neutron dosimeter in this study. After exposing to the neutron, the CR-39 detectors were prepared with the manufacturer's recommended etching conditions of 6.25 mol/L NaOH solution at a constant temperature of 85°C for 2 h and 50 min. The numbers of tracks were obtained from the automatic reader system and converted to $H^*(10)$ using calibration factor.

Response function simulation and validation

PHITS Monte Carlo code was used to simulate the response function of CUMOD by providing the proper geometry and material composition and irradiating it with a plane parallel beam of monoenergetic neutrons. The tally mode of dose deposit was selected for all four CR-39 dosimeters. The neutron energy was varied from 1 eV to 500 MeV. The number of initial neutrons was preferred to obtain <5% error of the tally results. The neutron response function of CUMOD between neutron energy and relative response to ^{241}AmBe along with fluence-to-ambient dose equivalent conversion coefficients[2] is illustrated in Figure 2. There is highly underresponse below 1 keV and overresponse in the energy range about 10–200 MeV. When compared to the energy response of WENDI-II,[14] there were about 60% underresponse around 0.1 MeV, 50% overresponse around 2 MeV, and also about 50% underresponse around 200 MeV.

The dose of CR-39 in CUMOD was calibrated with ^{241}AmBe source at the Office of Atom for Peace, Bangkok, Thailand. The neutron ambient dose equivalent rate was 115 μSv h^{-1}. The calibration was accomplished in the range of 100–1000 μSv. The linear relationship between $H^*(10)$ and the number of tracks as the calibration factor was demonstrated, as shown in Figure 3.

The validation of CUMOD response function was performed with the standard neuron source instead of the mono-energetic neutron beams due to the unavailability of the neutron beam in our country. The photoneutron beams in the energy range of 10 eV to 15 MeV[15] from Varian Clinac 23EX (Varian Medical System, Palo Alto, CA) and high energy neutron beams[8] from proton therapy machine were employed, as shown in Figure 4.

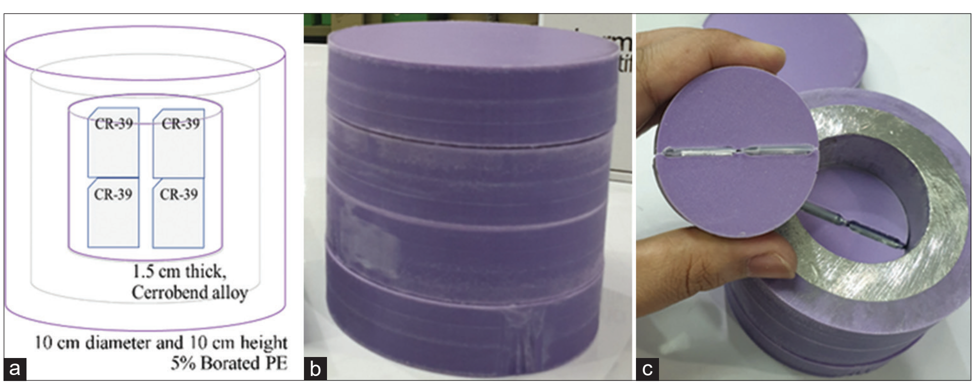

Figure 1: The Chulalongkorn University Neutron Moderator (CUMOD) neutron dosimeter (a) schematic diagram with CR-39, (b) fabricated CUMOD outside, and (c) fabricated CUMOD inside. CR-39: Poly allyl diglycol carbonate

Neutron ambient dose equivalent measurement

The lateral proton beam was selected for ease of the measurement setup. The isocenter was used to place at the surface of 30 cm × 30 cm × 35 cm solid water phantom which acted as the neutron source. The *H**(10) was measured at 100 cm distance and 0° (forward direction) with respect to the neutron source, as shown in Figure 5. WENDI-II has been used as the reference detector for *H**(10) evaluation.

Plan parameters

The treatment plans were generated using the beam scanning technique from Eclipse treatment planning system version 16.1.0 (Varian Medical System, Palo Alto, CA, USA). The treatment plans were separated into two scenarios. For the first scenario, the single energy dose plane of 10 cm × 10 cm field size at the depth of 10, 20, and 30 cm considering less neutron energy spreading. Then, the multiple energy treatment plans of 10 cm × 10 cm × 10 cm volume dose at the same as previous depths were generated considering its broad neutron energy range. For the volume dose treatment plan at 10 cm depth, the 5 cm range shifter was employed to get the full volume dose coverage. The dose distribution of all treatment plans is illustrated in Figure 6.

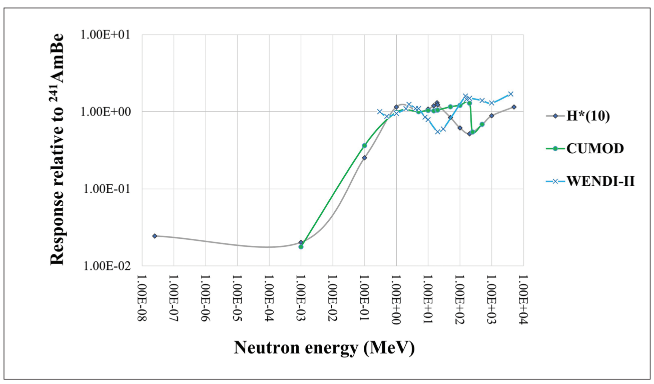

Figure 2: The response function of CUMOD (circle), *H**(10) conversion coefficient (diamond) and WENDI-II (cross) relative to ^{241}AmBe with the neutron energy range of 0.1–250 MeV. CUMOD: Chulalongkorn University neutron Moderator

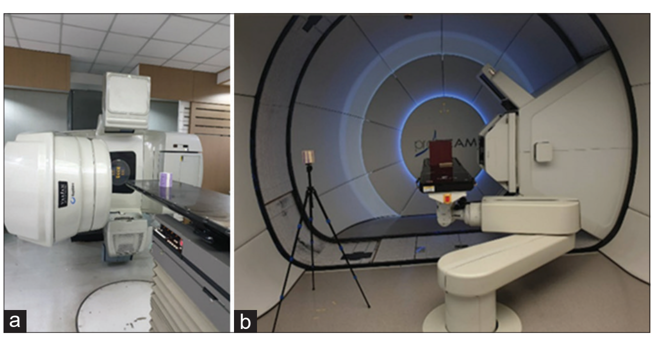

Figure 4: The measurement of *H**(10) (a) at 40 cm away from the isocenter of the 15 MV Varian Clinac 23EX with the closed collimator and (b) at 45° and 200 cm away from the isocenter of 140 MeV and 200 MeV proton beams from ProBEAM compact with 11 cm × 11 cm field size on 30 cm × 30 cm × 35 cm solid water phantom

All of the proton treatment plans were irradiated with the proton dose of 5 GyE.

Results

Response function validation

The results of the validation of CUMOD response function are illustrated in Table 1. The neutron energy range of 10 eV to 15 MeV showed *H**(10) per monitor unit (MU) from CUMOD was 0.7 µSv/MU. The results of *H**(10)/proton Gy from CUMOD were 3.1 µSv/Gy from the maximum neutron energy of 140 MeV, while *H**(10)/proton Gy from CUMOD was 13.7 µSv/Gy from the maximum neutron energy of 200 MeV.

Ambient dose equivalent

The neutron ambient dose equivalent from WENDI-II and CUMOD for all proton plans irradiated with the dose of 5 GyE are reported in Table 2. As the active detector, WENDI-II was used to detect the plan doses of *H**(10) higher than 100 µSv. The minimum detectability of CUMOD was considered to be 100 µSv, according to the property of CR-39 detector.[12] For single plane plans, the higher *H**(10) was found with deeper depth as well as the volume plans, as shown in Table 2. The *H**(10) of volume plans was also higher than single plane plan. The higher the energy and proton fluence, the higher number of the neutron ambient dose equivalent. Moreover, the *H**(10)

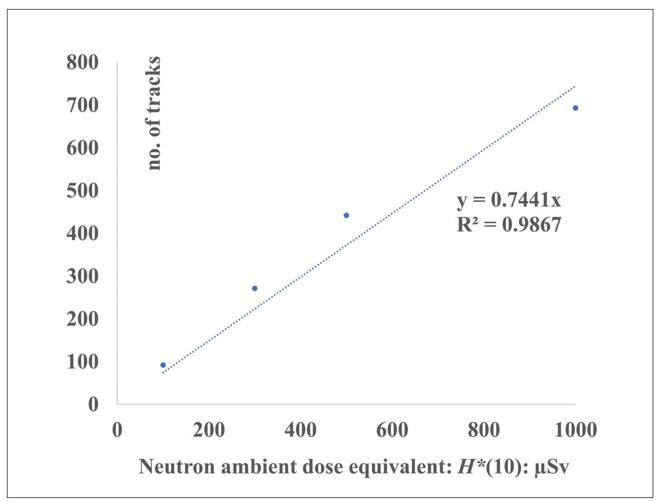

Figure 3: The calibration curve of Chulalongkorn University Neutron Moderator with ^{241}AmBe

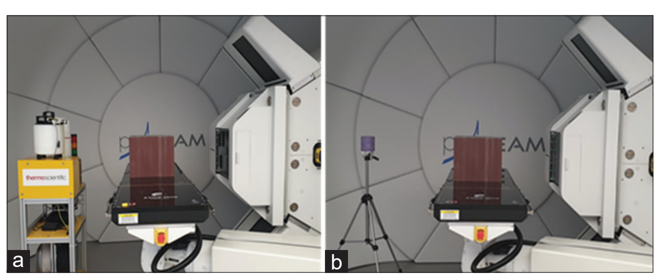

Figure 5: The experimental setup of (a) WENDI-II and (b) Chulalongkorn University Neutron Moderator with proton therapy system

Table 1: The Chulalongkorn University Neutron Moderator $H^*(10)$ in validation process

References		CUMOD $H^*(10)$				Difference (%)
Maximum energy*	Normalized $H^*(10)$	Irradiation	Average (μSv)	SD	Normalized $H^*(10)$	
15 MeV[15]	1.1 μSv/MU	2000 MU	1312	787	0.7 μSv/MU	−40
140 MeV[8]	3.2 μSv/Gy	80 Gy	246	88	3.1 μSv/Gy	−3
200 MeV[8]	11 μSv/Gy	30 Gy	412	290	13.7 μSv/Gy	25

*The maximum neutron energy of the neutron spectrum corresponds to maximum incident photon[15] and proton[8] energy. CUMOD $H^*(10)$: ChulalongkornUniversity Neutron Moderator Ambient dose equivalent, SD: Standard deviation, MU: Monitor unit

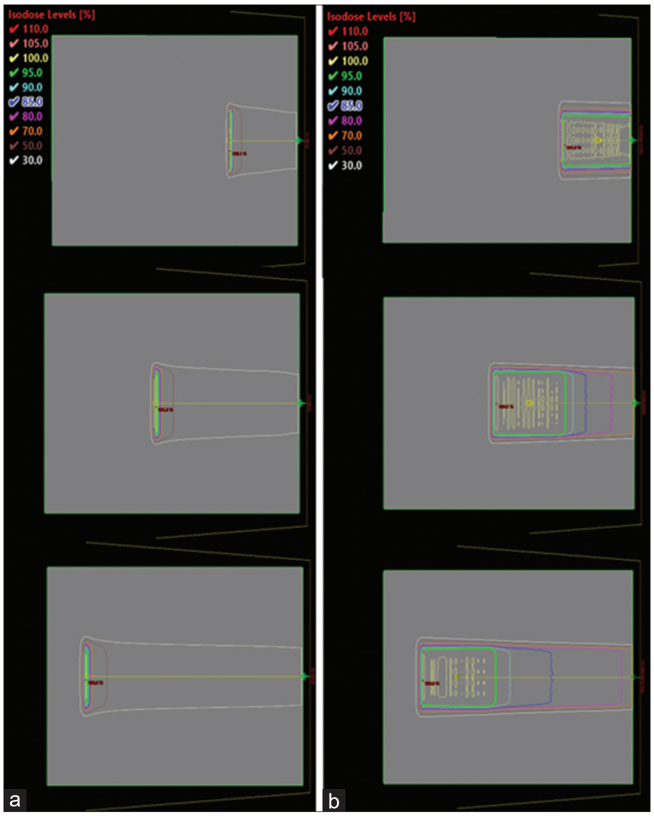

Figure 6: The dose distribution of (a) plane dose and (b) volume dose

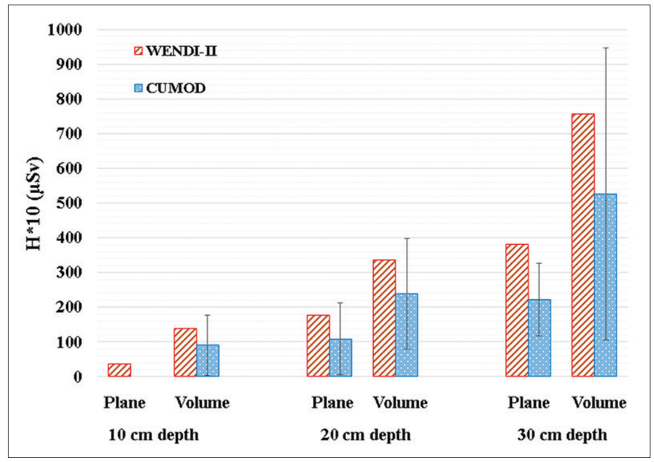

Figure 7: $H^*(10)$ of CUMOD and WENDI-II for different test plans. CUMOD: Chulalongkorn University Neutron Moderator

of CR-39 detectors in CUMOD showed together with that from WENDI-II as presented in Figure 7. The ambient dose equivalent value was normalized by the proton therapeutic dose ($H^*[10]/D$) for investigation and comparison.

Discussion

Several investigations have been carried out about the passive neutron detector with neutron moderator.[16-18] The Borated PE cylinder with Cerrobend alloy inside called CUMOD was designed to moderate the neutron energy to match with CR-39 detectors. The response functions of CUMOD were simulated from PHITS Monte Carlo code and validated using WENDI-II. The dose of CR-39 detectors in CUMOD was calibrated with ^{241}AmBe source and showed the linear response with R^2 of 0.9867, as shown in Figure 3. For the response function validation, the result of $H^*(10)$ per MU from CUMOD was 0.7 μSv/MU in neutron energy range of 10 eV to 15 MeV, which was about 40% lower than 1.1 μSv/MU from Howell *et al*., study[15] corresponding to the underresponse of CUMOD response function in the neutron energy range of 1–10 MeV. This difference might be due to the large deviation from the low normalized $H^*(10)$ of CR-39, the different neutron energy range from different Clinac models, and different neutron detector types. By comparing with Trinkl *et al.* study,[8] the result of $H^*(10)$/proton Gy from CUMOD was 3.1 μSv/Gy which was very good agreement to 3.2 μSv/Gy for 140 MeV. For 200 MeV, the result of $H^*(10)$/proton Gy from CUMOD was 13.7 μSv/Gy which was higher than 11 μSv/Gy (about 25%). For these two energies, the values agreed with the overresponse in the neutron energy range of 10–200 MeV.

For the ambient dose equivalent of CUMOD and WENDI-II in various plan types, it showed the same trend that the deeper depth had higher $H^*(10)$ and the volume plans also has higher $H^*(10)$ values. The relatively high standard deviation was observed similarly to the report of Infantino *et al*.[10] study. However, the plot of the $H^*(10)$ from WENDI-II and CUMOD has shown a linear relationship as demonstrated in Figure 7. A correction factor of 0.64 was found between the $H^*(10)$ responses between CUMOD and WENDI-II. For this measurement of neutron ambient dose equivalent, it is necessary to understand the neutron energy spectrum at the measurement location. The reported neutron spectrum, Trinkl *et al*.[8] showed that there were a few neutron peaks observed around the medium target, the evaporation peak (0.1–19.6 MeV), and the high energy peak (>19.6–250 MeV). The difference between the WENDI-II and CUMOD response

Table 2: The ambient dose equivalent from Wide-Energy Neutron Detector-II and Chulalongkorn University Neutron Moderator

Plan type	Depth (cm)	WENDI-II		CUMOD		
		$H^*(10)$ (μSv)	$H^*(10)/D$ (μSv/Gy)	$H^*(10)$ (μSv)	SD	$H^*(10)/D$ (μSv/Gy)
Plane	10	36.5	7.3	-	-	-
	20	176	35.2	109	104	21.8
	30	381	76.2	222	105	44.4
Volume	10	139	27.8	91	87	18.2
	20	337	67.4	239	159	47.8
	30	758	151.6	526	421	105.2

CUMOD: Chulalongkorn University Neutron Moderator. H*(10): Ambient dose equivalent. *H**(10)/D: Ambient dose equivalent per proton therapeutic dose

function over these energy ranges may be attributed to the two underestimate ranges of CUMOD observed in this study.

The ambient dose equivalent per proton therapeutic dose was also presented in Table 1 with the purpose of comparing to other studies.[8,15] This value depends on many factors such as the design of the nozzle, the volume of irradiation, the medium, the measured distance, and surrounded environment. The $H^*(10)/D$ of CUMOD varied from 0.022 to 0.105 mSv/Gy. The $H^*(10)/D$ results were comparable with the range of 0.0013–0.242 mSv/Gy from Charyyev and Wang[19] where the measurement was determined with WENDI-II for 9 cm × 9 cm PBS at the distance of 105 cm.

Conclusion

The CUMOD, as the passive detector, could be used well in our compact proton therapy. The ambient dose equivalent from CUMOD could be calculated to substitute with the value from the broad recognized neutron detector (WENDI-II). Further studies in various clinical conditions of $H^*(10)$ measurement are in progress to check the sustainability of using CUMOD in proton therapy centers.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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