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Secondary Neutron Dose Measurement for Proton Line Scanning Therapy

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Proton therapy is increasingly being actively used in the treatment of cancer. In contrast to photons, protons have the potential advantage of delivering higher doses to the cancerous tissue and lower doses to the surrounding normal tissue. However, a range shifter is needed to degrade the beam energy in order to apply the pencil beam scanning technique to tumors located close to the minimum range. The secondary neutrons are produced in the beam path including within the patient's body as a result of nuclear interactions. Therefore, unintended side effects may possibly occur. The research related to the secondary neutrons generated during proton therapy has been presented in a variety of studies worldwide, since 2007. In this study, we measured the magnitude of the secondary neutron dose depending on the location of the detector and the use of a range shifter at the beam nozzle of the proton scanning mode, which was recently installed. In addition, the production of secondary neutrons was measured and estimated as a function of the distance between the isocenter and detector. The neutron dose was measured using WENDI-II (Wide Energy Neutron Detection Instruments) and a Plastic Water phantom; a Zebra dosimeter and 4-cm-thick range shifter were also employed as a phantom. In conclusion, we need to consider the secondary neutron dose at proton scanning facilities to employ the range shifter reasonably and effectively.

Key Words: Proton therapy, Range shifter, Secondary neutron

Introduction

Proton therapy has been actively used to treat cancers and its use is increasing globally.[1,2] Currently, new proton therapy centers are under construction or being test-driven in the US, Japan, and the EU; plans for the construction of more accelerators are being considered.[3]

The Bragg peak, a unique property of a proton beam, is superior, compared to other cancer therapy techniques, in selectively transferring a relatively small dose to normal tissues and a maximum dose to tumor tissues.[4]

Proton therapy methods are largely divided into scattering methods and scanning methods. Despite numerous advantages in scattering methods, intensity modulated proton therapy (IMPT) using scanning is being currently receiving much attention, and most of the new proton therapy centers currently under construction apply scanning methods for treatment.

Although proton therapy, owing to its advantages, is used for treatments at numerous proton therapy centers, it has drawbacks. Protons interact with components in the nozzle in the beam path or with the nuclei of the patient, thereby generating secondary particles. The types of secondary particles include neutrons, protons, electrons, alpha particles, and heavier fragments. Secondary neutrons generated by a proton beam may cause other problems besides the patient treatment due to

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their high relative biological effectiveness (RBE) and penetrating power in comparison to other photons.[5,6]

Secondary neutrons are one of the major factors that cause the increase of the total dose and secondary cancers of patients by affecting the integral dose.[7] Secondary neutrons are commonly divided into external neutrons and internal neutrons, where external neutrons are defined as neutrons within the nozzle of a proton treatment device and internal neutrons are defined as neutrons generated by interactions between the proton beam and the patient.

Scanning methods, compared to scattering treatment methods, generate fewer secondary particles owing to the fact that there are fewer internal components within nozzle, such as the scattering foil and the modulator wheel. Various studies on secondary neutrons have been conducted around the world since 2007, reporting simulations or measurements of neutron emission from individual therapy centers.[8-10]

Study results vary from center to center, impairing direct comparisons. The results vary because individual centers have different proton therapy facility designs and beam conditions. Furthermore, scanning nozzles are designed slightly differently depending on their intended purpose, and the neutron doses resulting from different scanning nozzle designs should be considered, although research with such consideration is lacking. Furthermore, owing to the limit of the energy generated by the accelerators, a range shifter is required to treat near skin tumors, where protons transfer energy to the surrounding skin; however, there have been few studies on the impacts of neutrons with the use of range shifter.

Accordingly, to analyze shielding implications for secondary neutrons generated from a range shifter used in proton therapy equipment recently installed in South Korea, this study measured and assessed neutron emission based on the presence and location of a range shifter for a nozzle used in a scanning method. Furthermore, the study measured and assessed neutron emission based on the measurement distance of the detector.

Materials and Methods

A range shifter, in the context of cancer treatment, is a component that reduces the proton range by reducing the energy of the proton beam. The minimum energy of a proton beam, commonly available in proton therapy centers, is 70 MeV, which gives a depth of water propagation of 3.4 cm, which limits the treatment of near-skin tumors. When tumors are located close to the surface of the skin, the minimum range of the proton beam becomes a hurdle to treatment that may be overcome by lowering the proton range with a range shifter. In tumor treatments using a range shifter, materials are located on the beam path, generating additional nuclear reactions with protons and thereby producing secondary neutrons. Fig. 1 shows a range shifter used in proton therapy by the Samsung Medical Center in Seoul. The range shifter is 4 cm thick and made of polyethylene.

In this study, secondary neutron emissions were measured with the following equipment. The measurements were performed in the scanning gantry at the Samsung Medical Center in Seoul.[11] The gantry angle was 270° and phantoms were prepared with a Zebra dosimeter and Plastic Water. Neutron measuring devices were prepared with a WENDI-II (Wide Energy Neutron Detection Instrument, Thermo Scientific TM, USA) in which a He-3 detector is enclosed in a cylindrical polyethylene moderator (23 cm in diameter and 21 cm long). Table 1 corresponds to the technical specification of WENDI-II, and Fig. 2 depicts the WENDI-II used in the measurement.[12] This detector was calibrated at Enviro Korea, Co., Ltd. on September 23, 2015.

The first experiment measured neutron emission, based on

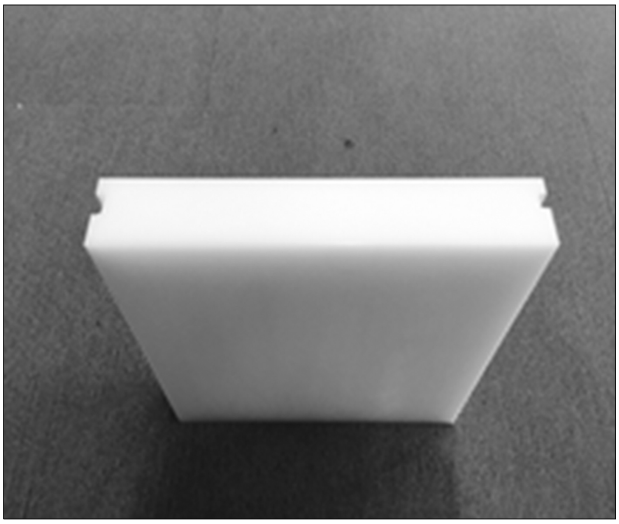


Fig. 1. Range shifter.

Table 1. WENDI-II technical specification.

Measuring range	0.01 μSv/h to 100 mSv/h Cf-252	Gamma-sensitivity	1 to 5 μSv/h at 100 mSv/h, 662 keV
Sensitivity	0.84 cps/(μSv/h) Cf-252	Ambient temperature	−30 to +50°C
Energy range	25 meV to 5 GeV according to ICRP 74 (1996)	Humidity	Up to 90% non-condensing
Angular dependence	±20% all directions	Atmospheric pressure	500 to 1,500 hPa
Linearity	±20%	Height	320 mm (12.6″)
Diameter	230 mm (9″)	Weighting range	13.5 kg (29.8 lb)

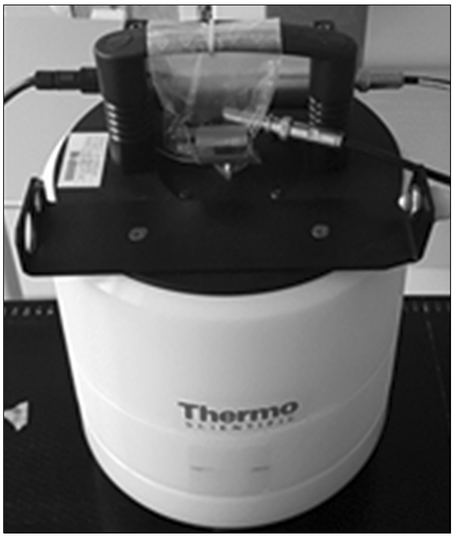


Fig. 2. WENDI-II detector.

the distance between the neutron source and the detector, generated by a phantom in scanning treatment as follows. The volume of the Plastic Water phantom was 30×30×24.7 cm^3, located at the isocenter. The phantom was irradiated by a proton beam at 230 MeV, the highest energy, to obtain the highest possible secondary neutron flux, and the secondary neutron emission generated by the phantom was measured according to distance between the neutron source and the detector. Neutron measurements were obtained at distances of 40, 60, 90, and 110 cm from the isocenter in the beam's transaxial direction, and at distances of −50, −75, and −100 cm from the isocenter in the beam's radial direction. Fig. 3 shows a schematic of this experimental setup.

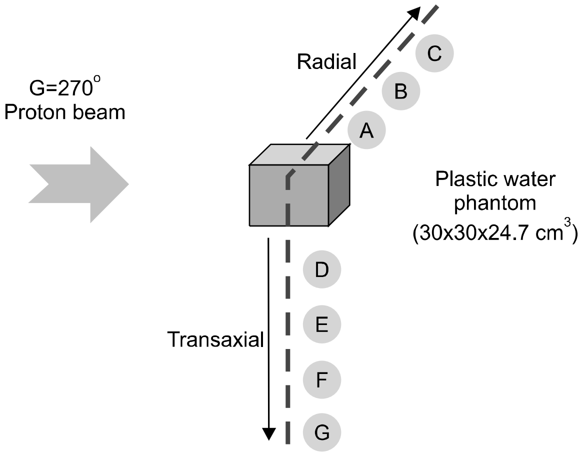


Fig. 3. Schematic of first experiment.

The second experiment measured neutron emission from the range shifter used in scanning treatment, according to the location of the detector as follows. After the Zebra detector was placed at the proton isocenter, the WENDI-II was placed at the first location, 100 cm in the axial direction from the isocenter, where the secondary neutron emission was measured according to presence of a range shifter. The WENDI- II was then placed at the second measurement location, −25 cm in the axial direction, and 30 cm in the radial direction from the isocenter, where the measurements were performed again. Fig. 4 is a schematic of this experiment and Fig. 5 describes the four proton scanning beam conditions used.

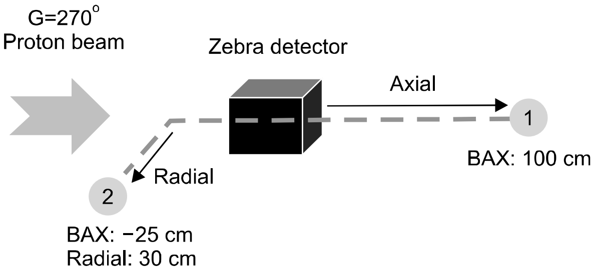
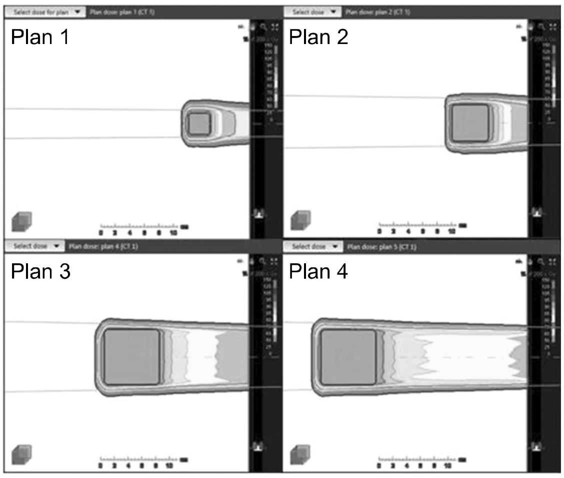


Fig. 4. Schematic of second experiment.

Fig. 6 shows the individual measurement locations of the



	Cube size (cm^3)	Target center (cm)
Plan 1	3x3x3	7
Plan 2	5x5x5	8
Plan 3	8x8x8	17
Plan 4	8x8x8	26

Fig. 5. Two-dimensional dosage distribution within phantom irradiated by four proton scanning methods to assess neutron dose of range shifter.

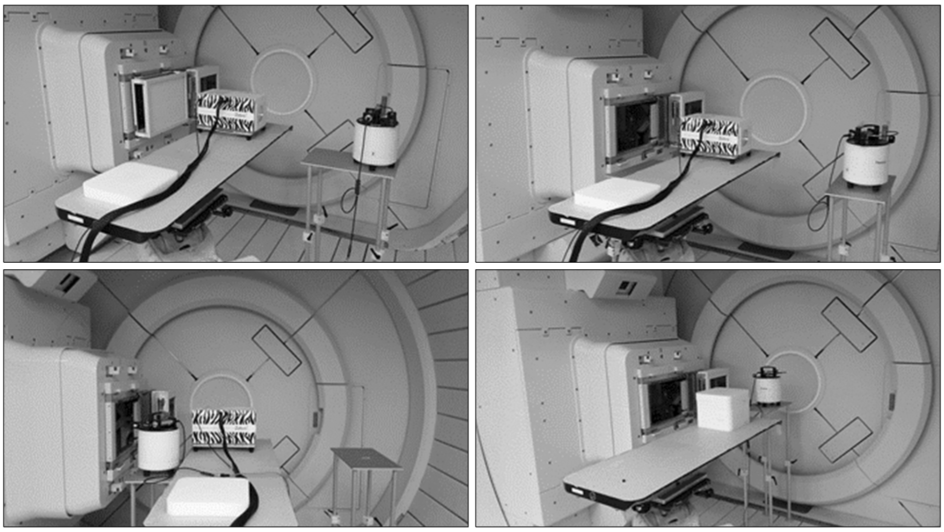


Fig. 6. Measurement of secondary neutron using WENDI-II. Upper left and right: neutron emission measurements taken with a range shifter; lower left: emission measurement taken without a range shifter; lower right: emission measurements taken from a phantom.

experimental processes. The two upper figures in Fig. 6 correspond to neutron dose measurements based on the presence of a range shifter, and the lower left figure corresponds to measurements at another location without a range shifter. The lower right figure shows neutron emission measurements obtained from a phantom according to detector measurement distance in an actual experiment.

Results

In the first experiment, the Plastic Water phantom, located at the isocenter, was irradiated with a 230 MeV proton beam; the neutron dose was obtained at varying distance. Table 2 shows measurements of the secondary neutron emission from the isocenter in (1) the radial direction and (2) the transaxial direction. As shown in the table, as the distance increases, the secondary neutron dose decreases. This showed a similar, although not identical, trend to the $1/r^2$ values obtained according to the distance. Figs. 7 and 8 are graphical representations of Table 2, showing the secondary neutron dose according to the distance in the same direction.

Table 3 shows the measurements of the neutron dose both with and without the range shifter with the detector in the first position. Although the neutron dose behind the phantom in the direction of the proton motion is extremely low, the neutron dose is higher without a range shifter, except for in Plan 1.

Table 2. Secondary neutron dose of a plastic water phantom at varying distance.

Energy (MeV)	230 MeV						
Field size	$10\times10\times10$ cm^3						
Gantry angle	270°						
Phantom	Plastic Water phantom ($30\times30\times24.7$ cm^3)						
Position	A	B	C	D	E	F	G
Detected WENDI-II position	Radial: −50 cm	Radial: −75 cm	Radial: −100 cm	Trans axial: −40 cm	Trans axial: −60 cm	Trans axial: −90 cm	Trans axial: −110 cm
Neutron dose (mSv/Gy)	0.219	0.110	0.076	0.269	0.150	0.094	0.069

Table 3. Secondary neutron dose of dedicated scanning nozzle using range shifter position 1.

Plan no.	1	2	3	4	
Proton range (cm)	8.5	19.5	21	30	
SOBP (cm)	3	5	8	8	
Detected WENDI-II position	BAX: 100 cm				
Neutron dose (mSv/Gy)	0.033	0.017	0.161	0.377	With 4 cm range shifter
Neutron dose (mSv/Gy)	0.009	0.088	0.219	0.461	Without 4 cm range shifter

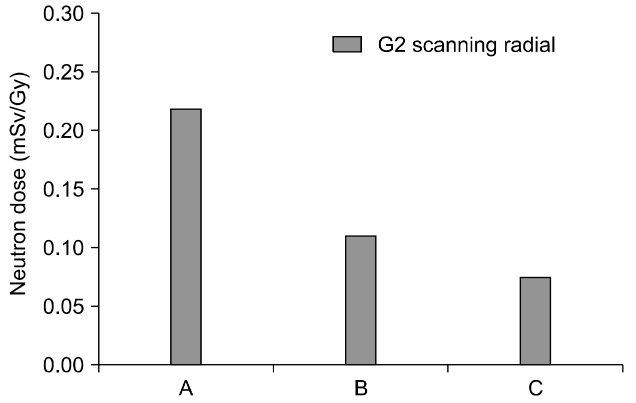


Fig. 7. Secondary neutron dose on the radial axis from isocenter.

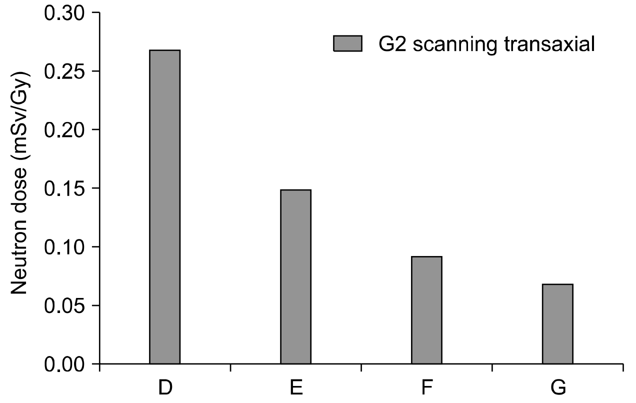


Fig. 8. Secondary neutron dose on the beam axis from the isocenter.

The reason for this may be that a lower range affected neutron emission. However, the neutron emission was increased at the location of Plan 1, where the spread out bragg-peak is less than 4 cm long owing to the use of a 4-cm-thick range shifter.

On the other hand, the measurements at the side position of the range shifter confirmed that neutron dose increased overall with the presence of a range shifter because all secondary neutrons generated from nuclear reactions between the proton beam and the range shift could be measured when the measurement detector was located immediately behind the range shifter. Thus, if a patient were positioned here, the use of a range shifter would affect the increase in the neutron dose by a small amount. This study has confirmed that the neutron dose increases by a maximum of 39.3% at the location in Plan 2. Furthermore, as shown in Table 4, as the volume irradiated with protons increases, the neutron emission increases; the neutron dose within the same volume is higher when the penetration depth of the protons is large. Figs. 9 and 10 are graphical representations of Tables 3 and 4, respectively.

Table 4. Secondary neutron dose of dedicated scanning nozzle using range shifter position 2.

Plan no.	1	2	3	4	
Proton range (cm)	8.5	19.5	21	30	
SOBP (cm)	3	5	8	8	
Detected WENDI-II position		BAX: −25 cm Radial: 30 cm			
Neutron dose (mSv/Gy)	0.028	0.085	0.324	0.456	With 4 cm range shifter
Neutron dose (mSv/Gy)	0.024	0.061	0.269	0.370	Without 4 cm range shifter

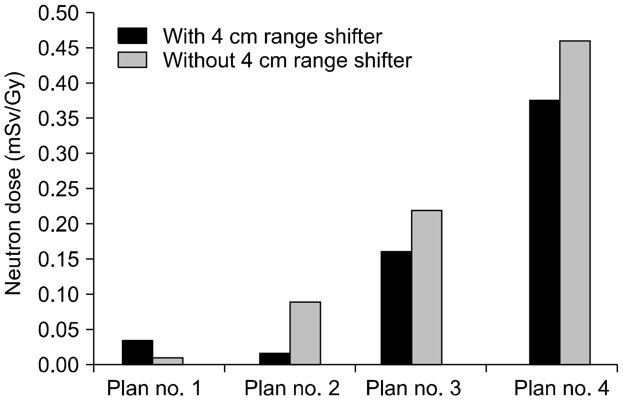


Fig. 9. Value of secondary neutron/Exp_1.

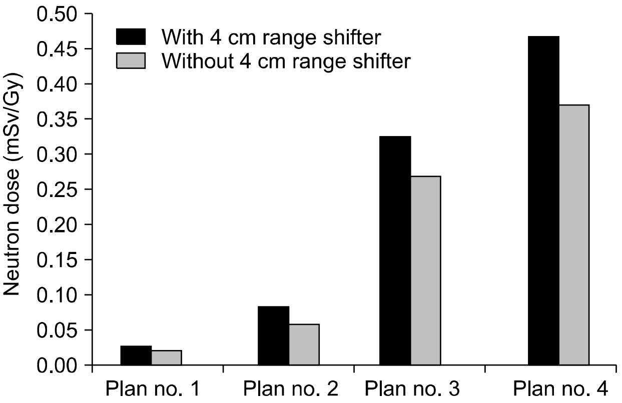


Fig. 10. Value of secondary neutron/Exp_2.

Conclusion

This study measured neutron emission in scanning treatment, and its relation to detector distance and the presence of a range shifter at the scanning gantry at the Samsung Proton Therapy Center in Seoul.

The measurement of the secondary neutron emission from a Plastic Water phantom in two directions confirmed that secondary neutron emission decreased as detection distance increased. This showed a similar, though not identical, trend to the $1/r^2$ values obtained at varying distance.

The experiment based on the presence of a range shifter confirmed that the range shifter affected the increase in secondary neutrons. Although the results depended on measurement locations, the presence of a range shifter, at the same location, resulted in the neutron dose increasing by a maximum of 39.3%.

Although scanning treatment is known to generate less neutron emission than scattering methods, from the ALARA (As Low As Reasonably Achievable) perspective, shielding measures must be established to reduce unnecessary radiation exposure to patients.[13)]

Therefore, shield planning could reasonably reduce unnecessary radiation exposure to patients by considering the results from this study at the stage of treatment planning. Furthermore, the next study plans to investigate secondary neutron emission based on the types and thickness of range shifters through FLUKA Monte Carlo simulation code, further exploring shielding measures of secondary neutrons. The results from this study may provide resources for other institutions to explore shielding of neutron emission from a range shifter during proton scanning treatment, and the results may help to reduce unnecessary radiation exposure when treating patients.

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