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The neutron dose equivalent evaluation and shielding at the maze entrance of a Varian Clinac 23EX treatment room

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Purpose: To evaluate the neutron and photon dose equivalent rate ($H_{n,D}$ and H_G) at the outer maze entrance and the adjacent treatment console area after the installation of a Varian Clinac 23EX accelerator with a higher beam energy than its predecessor. The evaluation was based on measurements and comparison with several empirical calculations. The effectiveness of borated polyethylene (BPE) boards, as a maze wall lining material, on neutron dose and photon dose reduction is also reported.
Methods: A single energy Varian 6 MV photon linear accelerator (linac) was replaced with a Varian Clinac 23EX accelerator capable of producing 18 MV photons in a vault originally designed for the former accelerator. In order to evaluate and redesign the shielding of the vault, the neutron dose equivalent $H_{n,D}$ was measured using an Andersson–Braun neutron Rem meter and the photon dose equivalent H_G was measured using a Geiger Müller and an ion chamber γ-ray survey meter at the outer maze entrance. The measurement data were compared to semiempirical calculations such as the Kersey method, the modified Kersey method, and a newly proposed method by Falcão *et al.* Additional measurements were taken after BPE boards were installed on the maze walls as a neutron absorption lining material.
Results: With the gantry head tilted close to the inner maze entrance and with the jaws closed, both neutron dose equivalent and photon dose equivalent reached their maximum. Compared to the measurement results, the Kersey method overestimates the neutron dose equivalent $H_{n,D}$ by about two to four times (calculation/measurement ratio$\approx$2.4–3.8). Falcão's method largely overestimates the $H_{n,D}$ (calculation/measurement ratio$\approx$3.9–5.5). The modified Kersey method has a calculation to measurement ratio about 0.6–0.9. The photon dose equivalent calculation including McGinley's capture gamma dose equivalent equation estimates about 77%–98% of the measurement. After applying BPE boards as a lining material on the inner corner of the maze wall, the $H_{n,D}$ and the H_G at maze entrance were decreased by 41% and 59%, respectively.
Conclusions: This work indicates that the Kersey method overestimates the neutron dose equivalent $H_{n,D}$ for a Varian Clinac 23EX accelerator. The Falcão method overestimates the $H_{n,D}$ partially due to the discrepancy in the International Commission on Radiological Protection (ICRP) conversion factors caused by the uncertainties of the estimated average neutron energy. The modified Kersey method gives the closest estimation of a Varian Clinac 23EX accelerator operated at 18 MV photon mode in a maze with a similar design as in the authors' study. However, it should be used with caution because of its tendency to underestimate the $H_{n,D}$. A borated polyethylene lining can provide a cost effective method to reduce neutron and photon dose equivalent at the maze door for an existing linac vault, following the installation of a higher energy linac. © *2011 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3533713]

Key words: medical accelerator maze, photoneutrons, semiempirical calculations, shielding

I. INTRODUCTION

When the beam energy of clinical linear accelerators (linacs) is greater than 10 MeV, the neutron dose and the neutron shielding for operating personnel cannot be neglected.[1–3] It is important to study the neutron dose at the maze entrance and the corresponding shielding method for the linacs working at a high energy above this threshold. The neutron dose as well as the accompanying photon dose at the maze entrance has been studied for many years by Monte Carlo simulations,[4–6] semiempirical analysis,[6–10] and measurements.[4,8,10–13] Monte Carlo simulations are capable of providing a variety of dose information in advance. However, an accurate neutron spectrum simulation is required, with detailed information on the geometry and the materials of the linac head and the treatment room. Monte Carlo neutron simulations generally involve elaborated programming and computation. Thus, semiempirical calculations are often preferred for neutron dose evaluation and shielding verification due to its simplicity and less time consumption. Normally, these calculations relate the neutron dose equivalent at the maze entrance to the x-ray absorbed dose at isocenter. A semiempirical calculation of the dose equivalent at the maze door is easily achievable when the beam dose rate is known. However, the applicability of parameters in semiempirical equations is limited by the type of machine, the geometry of treatment vault, and the shielding material used in the studies. Direct measurements for different linac models are required to examine and support semiempirical calculation methods.

The relationship between neutron dose equivalent and the absorbed dose at isocenter has been intensely studied by several research groups.[6,9,12–17] The parameters of neutron source strength (Q_n), neutron dose equivalent (H_0) near the isocenter, and tenth value distance (TVD) on commonly used medical accelerators under different vault and maze shielding conditions were provided. The studies include linacs manufactured by Elekta,[12] General Electric,[6,12–14,17] Mitsubishi,[14] Philips,[9,12,14,16] Siemens,[6,12–14] Toshiba,[14] and Varian.[6,9,12–15] However, the relationship between the neutron dose equivalent at the maze door and the absorbed dose from the photon beam for new linac models, including the Varian Clinac 23EX (Varian Medical Systems, Inc., Palo Alto, CA), has not been thoroughly evaluated. A study of the neutron dose equivalent at the maze entrance will provide information for neutron dose equivalent evaluation for this frequently encountered linac. In addition, the parameters extracted from the shielding measurement should be applicable to a machine working with similar parameters and maze design.

This work reports the measurement of neutron dose equivalent at the outer maze entrance and the console area adjacent to the neighboring vault after the installation of a Varian Clinac 23EX accelerator with a higher beam energy than the predecessor. The measurement data were compared to semiempirical calculation results obtained by the Kersey method,[7] the modified Kersey method,[10] and a newly proposed method by Falcão el al.[6] The measurements were taken before and after lining the maze wall with borated polyethylene (BPE) boards. The effectiveness of this neutron absorption material (BPE) on neutron dose and photon dose reduction was reported. In addition, the photon dose at the maze entrance was measured and compared with calculations.

II. METHODS AND MATERIALS

II.A. Theory

Kersey proposed one of the earliest techniques to evaluate the neutron dose equivalent at a maze entrance.[7] According to this method, the neutron dose equivalent at the maze entrance per unit absorbed dose due to x-rays at the isocenter ($H_{n,D}$), expressed in mSv Gy^{-1}, is given by

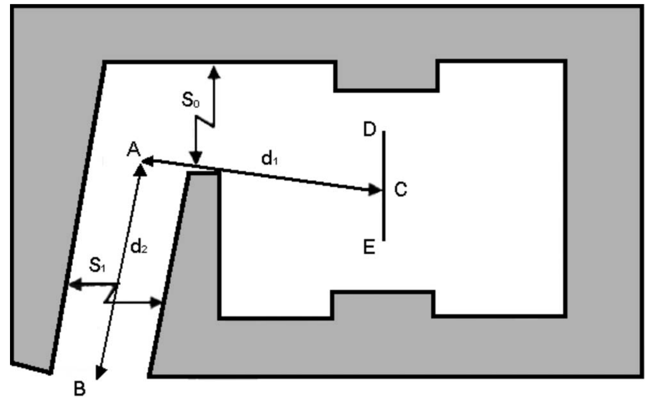

FIG. 1. Scheme of the vault for the semiempirical calculations. The distance d_1 is from the isocenter C to the point A on the maze centerline from which the isocenter is just visible. The distance d_2 is from the point A to the outside of the maze door (point B). The inner maze entrance cross-sectional area and the cross-sectional area along the maze are denoted by S_0 and S_1, respectively. When the gantry angle is 270°, the beam is directed from point D toward point E.

$$H_{n,D} = H_0\left(\frac{S_0}{S_1}\right)\left(\frac{d_0}{d_1}\right)^2 10^{-(d_2/5)}, \quad (1)$$

where H_0 is the total neutron dose equivalent at a distance d_0 (1.41 m) from the target per unit absorbed dose of x-ray at the isocenter (mSv Gy^{-1}); d_0 is the distance from the target to a point, located in a horizontal plane 100 cm from the target and is 1 m perpendicular away from the axis of a beam at 180° gantry angle [see Followill *et al.* for Fig. 1 (Ref. 12)]; d_1 is the distance measured from the isocenter C to the point A on the maze centerline from which the isocenter is just visible (Fig. 1); d_2 is the distance from the point A to the outside of the maze door (point B); S_0 is the inner maze entrance cross-sectional area; and S_1 is the cross-sectional area along the maze. This equation is based on the assumption that the maze has a TVD of 5 m for the attenuation of neutrons in the maze.

McGinley *et al.*[9] pointed out that the $H_{n,D}$ could be resolved into the sum of two exponential functions, i.e., neutron dose equivalent decreases exponentially with d_2 with two different TVDs. Wu and McGinley[10] further proposed an equation with consideration of nonstandard surface areas or mazes with exceptional width or length. The neutron dose equivalent at the outside maze entrance is then given as the modified Kersey method by the following equation:

$$H_{n,D} = 2.4 \times 10^{-15}\varphi_A \sqrt{\frac{S_0}{S_1}}[1.64 \times 10^{-(d_2/1.9)} + 10^{-(d_2/\mathrm{TVD})}], \quad (2)$$

where $H_{n,D}$ is expressed in Sv Gy^{-1} and φ_A represents the neutron fluence at the inner maze entrance per unit absorbed dose of photons (m^{-2} Gy^{-1}) at the isocenter[18–20] and can be determined according to

$$\varphi_A = \frac{\beta Q_n}{4\pi d_1^2} + \frac{5.4\beta Q_n}{2\pi S_r} + \frac{1.26 Q_n}{2\pi S_r}, \quad (3)$$

where β is the transmission factor for neutrons that penetrate the head shielding (1.0 for lead and 0.85 for tungsten head shielding), Q_n is the neutron source strength in neutrons emitted from the accelerator head per Gray of x-ray absorbed dose at the isocenter,[12,19] and S_r is the surface area of the treatment room (m^2).

The TVD in Eq. (2) is the tenth value distance of the neutron attenuation in the maze expressed in meters. It is proportional to the square root of the cross-sectional area along the maze S_1 (m^2)

$$\text{TVD} = 2.06\sqrt{S_1}. \quad (4)$$

Recently, Falcão *et al.*[6] proposed another equation,

$$\text{TVD} = 1.7 + 0.55 S_1, \quad (5)$$

to estimate the tenth value distance without resolving the neutron fluence into two components. They suggested converting neutron fluence to dose at the inner entrance of the maze, using the conversion factor given by the International Commission on Radiological Protection (ICRP) Publication 74.[21] According to Falcão *et al.*'s observation, the fluence should be multiplied by 2 before the conversion. Then the $H_{n,D}$ at the entrance can be calculated by using the TVD value given by Eq. (5).

The dose equivalent due to the neutron capture γ-rays (h_φ) is a major component of the total photon dose equivalent H_G at the door. McGinley *et al.*[9] proposed a method to calculate the neutron capture gamma dose equivalent. According to the method, the dose equivalent from the neutron capture γ-rays at the outer maze entrance per unit absorbed dose of x-rays at the isocenter is given by

$$h_\varphi = K\varphi_A 10^{-(d_2/\text{TVD})}, \quad (6)$$

where the TVD is 5.4 m for x-ray beams in the range of 18–25 MV and K is the ratio of the neutron capture gamma dose equivalent to the total neutron fluence and is 6.9×10^{-16} Sv m^2 as suggested in NCRP Report No. 151.[22] Other components of the H_G include the dose equivalent due to the scattering of the primary beam from the room surfaces (H_S), the primary beam scattered from the patient or phantom (H_{ps}), the scattered head leakage photons (H_{LS}), and the leakage radiation which is transmitted through the inner maze wall (H_{LT}). These four components (H_S, H_{ps}, H_{LS}, and H_{LT}) can be calculated using the formulae for maze door dose equivalent calculations as described in NCRP Report No. 151.

In the Kersey method calculation, as described in Eq. (1), the H_0 values were taken as 1.02–1.6 mSv Gy^{-1} in this study. These are the values suggested by McGinley *et al.*[19] for Varian 1800 linacs (Varian Medical Systems, Inc., Palo Alto, CA) which have a similar gantry head design with the Varian Clinac 23EX. In the modified Kersey method and neutron capture gamma dose equivalent calculations, the Q_n used in the calculation of the φ_A was taken as from 0.87×10^{12} to 1.22×10^{12} Gy^{-1}, as suggested by McGinley *et al.* for Varian 1800 linacs[19] and by Followill *et al.* for Varian 2100C linacs[12] (Varian Medical Systems, Inc., Palo Alto, CA), which also have a similar gantry head design. These are the widely used values for shielding calculations recommended in NCRP Report No. 151. The surface area of the treatment room (S_r) was estimated by the surface area of the concrete walls including the ceiling and floor. In the Falcão method calculation, the average neutron energy used to get the neutron fluence to dose equivalent conversion factor from ICRP Publication 74 (Ref. 21) was taken as 0.1 MeV, as suggested by Falcão *et al.*

II.B. Survey meters and measurement parameters

In this study, we used a Rem meter (AN/PDR-70NRC NP-2, Nuclear Research Corporation, Southampton, PA) as the neutron dose survey meter. Its design is based on the study of Anderson and Braun.[23] The NP-2 Rem meter has an energy response curve which simulates the ICRP fluence to dose equivalent conversion factor within a factor of 1.0–2.0 in the energy range from 0.025 eV (thermal) to 5 MeV (data from manufacturer). McCall and Swanson[24] pointed out that the photoneutron spectrum outside a concrete shielding resembles a heavily shielded fission spectrum and the average energy drop is obvious. According to studies of Kry *et al.* and Howell *et al.* on a Varian Clinac 21EX accelerator (Varian Medical Systems, Inc., Palo Alto, CA) operating at 15, 18, and 20 MV, the neutron spectrum at 40 cm from the isocenter has a maximum energy below 10 MeV and the average neutron energy was reported between 0.24 and 0.61 MeV.[25,26] Liu *et al.*[27] reported that the average neutron energy could be as low as 0.5 MeV at 1 m away from the gantry head of an 18 MV linac. Based on these published reports, we have assumed that the neutron spectrum at the maze entrance has an average energy lower than 0.5 MeV. Hence, the NP-2 Rem meter is suitable for neutron field measurement outside of a concrete treatment room.

A Ludlum 14C survey meter with a Model 44-6 sidewall Geiger Müller probe (Ludlum Measurements, Inc., Sweetwater,TX) and a Victoreen 450P pressurized ion chamber survey meter (Victoreen, Inc., Cleveland, OH) were used at the same time to measure the photon dose equivalent H_G. The results from these two photon dose survey meters were crosschecked with each other during the measurement and are in good agreement (within 8%). The dose equivalent readings from the two meters were averaged to get the mean value.

All the measurements were taken at 0.9 m above the floor. The maze entrance measurements were taken at 0.3 m away from the maze door (point B in Fig. 2) on the maze centerline. The adjacent treatment console area measurements were taken at 4.0 m away from the maze door and 0.4 m inside of the console area entrance (point F in Fig. 2), where the maze door is just visible. The points A–E in Fig. 2 are the same with the points A–E shown in Fig. 1. The lengths of AB (the d_2 in Fig. 1) and AC (the d_1 in Fig. 1) are 5.3 m and 6.1 m, respectively.

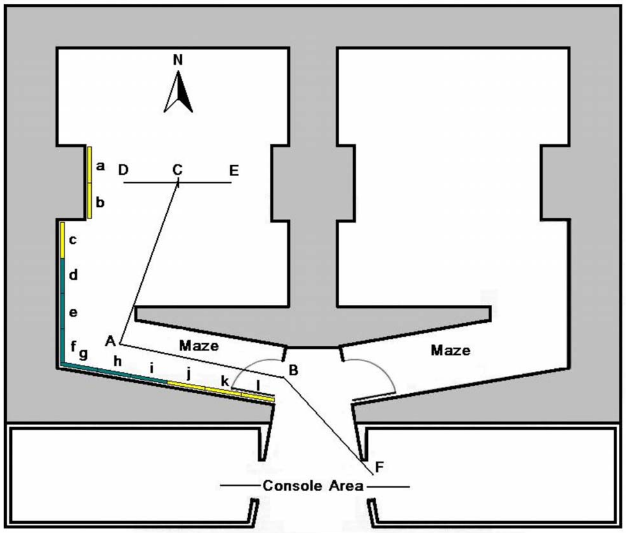

FIG. 2. Scheme of the point of measurement in this study. The letters from a to l represent the possible BPE board locations in the maze. The locations d–i are where the BPE boards were finally installed. Points A–E are the same to those in Fig. 1. When the gantry angle is 270°, the gantry head is close to the west wall and the beam is directed from point D toward point E.

The neutron dose equivalent measurement uncertainty was estimated to be ±15% in this study. The photon dose equivalent measurement uncertainty was estimated to be ±11%. The measurement uncertainty is composed of the uncertainties from the meter calibration, the measurement geometry (such as the measurement distance and the angular dependence of the meters), and the repeatability of measurement readings.

II.C. Shielding

The maze door in this study is made of 0.64 cm (0.25 in) thick tempered glass. The major function of the maze door is to act as a safety interlock. Its interaction with the photon and neutron field was ignored. After replacing the old linac (with 6 MV photon beam only) with the new dual energy Varian Clinac 23 EX accelerator (with 6 MV and 18 MV photon beam), the increment of neutron and photon dose equivalent required further shielding at the maze door and its peripheral region. A new shielding door at the maze entrance used to reduce the dose equivalent was proposed. However, the application of using borated polyethylene boards was found to be more economical and feasible. Six pieces of borated polyethylene boards (5% boron element in weight in the form of boric oxide, NELCO, Inc., Woburn, MA) were secured to the maze wall using metal screws at positions d–i as seen in Fig. 2. Each board has a size of $2.5\times 244 \times 122\ \text{cm}^3$ ($1\times 48\times 96\ \text{in}^3$). The high concentration of hydrogen in polyethylene made it an effective material to thermalize fast neutrons. The ^{10}B in the BPE boards has very high thermal neutron absorption cross section (σ=3840 b). Therefore, the BPE is a very effective material for neutron shielding. The neutron capture γ-rays produced by the maze wall will also decrease with the neutron fluence. However, a

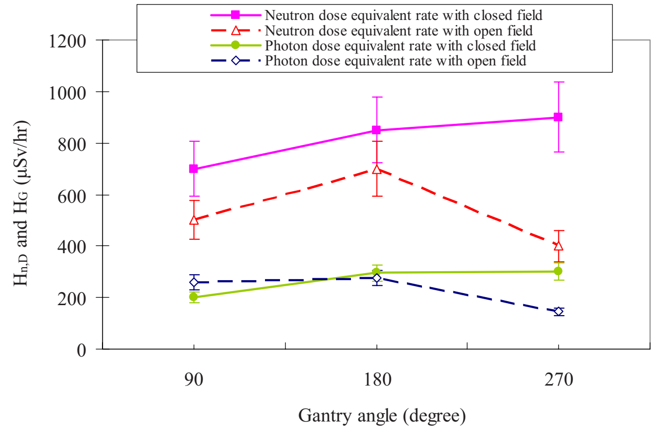

FIG. 3. The measured $H_{n,D}$ and H_G with different gantry angles and jaw settings. The closed and open fields correspond to a field size of 0.5×0.5 and $40\times 40\ \text{cm}^2$, respectively. Both units of the $H_{n,D}$ and the H_G were converted to dose equivalent rate (μSv h^{-1}).

478 keV γ-ray will be emitted from ^{7}Li after the neutron absorption, which increases the total photon dose equivalent rate.

III. RESULTS

III.A. Measurements

A series of measurements was first carried out to find the conditions of the Varian Clinac 23EX accelerator that produces the largest dose equivalent rate at the door (point B in Fig. 2). The linac was operated at 18 MV photon mode with output dose rate of 600 MU min^{-1}, which is the maximum output rate of the linac. The beam irradiated a $30\times 30 \times 20\ \text{cm}^3$ acrylic phantom at 90°, 180°, and 270° gantry angles, respectively. The centroid of the phantom was placed at the isocenter. The field sizes were set at 40×40 (open jaw setting) and $0.5\times 0.5\ \text{cm}^2$ (closed jaw setting).

In order to make a direct comparison between the results of measurements (in mR h^{-1} or mrem h^{-1}) and calculations (in Sv Gy^{-1} or mSv Gy^{-1}), both units of the $H_{n,D}$ and the H_G were converted to dose equivalent rate, μSv h^{-1} in this paper. The measurement unit mR h^{-1} was taken as equivalent to mrem h^{-1} (10 μSv h^{-1}) in soft tissue. The quality factor is 1 for photons. The calculation unit Sv Gy^{-1} or mSv Gy^{-1} was converted to μSv h^{-1} using the linac output dose rate (600 MU min^{-1}).

III.A.1. Neutron dose equivalent

The measured neutron dose equivalent $H_{n,D}$ was shown as a function of the gantry angles in Fig. 3. When the jaws are open, the $H_{n,D}$ increases from 500 to 700 μSv h^{-1} as the gantry angle changes from 90° to 180°, where 180° is with the beam aiming toward the floor. The neutron dose equivalent decreases to 400 μSv h^{-1} when the gantry angle changes to 270°. With the jaws closed, the $H_{n,D}$ increases with the gantry angle (when the gantry head gets close to the inner maze entrance). The $H_{n,D}$ at 90°, 180°, and 270° are 700, 850, and 900 μSv h^{-1}, respectively.

TABLE I. Comparison of the measured dose equivalent and the calculation results at the maze entrance of the Varian Clinac 23EX accelerator. The measurement results and the calculation to measurement ratios were shown with uncertainties (in parenthesis).

	Photon H_G (μSv h^{-1})	Neutron $H_{n,D}$ (μSv h^{-1})		
		Kersey	Modified Kersey	Falcão
Measurement	305 (34)	925 (139)	925 (139)	925 (139)
Calculation	234–298	2251–3532	585–820	3611–5063
Ratio	0.77(8)–0.98(11)	2.43(36)–3.82(57)	0.63(9)–0.89(13)	3.90(59)–5.47(82)

III.A.2. Photon dose equivalent

The measurement results of the total photon dose equivalent H_G were also shown as a function of the gantry angles in Fig. 3. During the measurements, the scattering and leakage photons as well as the neutron capture γ-rays were detected and they were not distinguishable from each other in the photon survey meters. With the maximum jaw openings (40×40 cm^2), the H_G is 260 and 145 μSv h^{-1}, respectively, for 90° and 270° gantry angles. The H_G reaches its maximum (275 μSv h^{-1}) of the largest open jaw settings at the 180° gantry angle. When the jaws are closed, the H_G at 90°, 180°, and 270° are 200, 295, and 300 μSv h^{-1}, respectively.

III.A.3. Maximum reading setup

A similar trend of dose equivalent as a function of gantry angle was observed for both neutrons and photons. Both the $H_{n,D}$ and the H_G reach their maximum at 180° gantry angle when the jaws are open and at 270° when the jaws were closed. The results show that the $H_{n,D}$ and the H_G at the door are at their overall maximum when the gantry is at 270° and with the jaws closed (0.5×0.5 cm^2) (Fig. 3). At the gantry angle 270°, the gantry head is close to the west wall and the inner maze entrance and the beam is directed from point D toward point E (Fig. 2).

III.B. Semiempirical calculations

The maximum of the calculated total photon dose equivalent (H_G) is the sum of its five components: H_S, H_{ps}, H_{LS}, H_{LT}, and h_φ. Based on Eq. (6) with different values for Q_n ($0.87\times10^{12}-1.22\times10^{12}$ Gy^{-1}), the calculated neutron capture gamma dose equivalent h_φ is $159-223$ μSv h^{-1}. Based on the formulae in NCRP Report No. 151 for maze door dose equivalent calculations, the dose equivalent due to the scattering of the primary beam from the room surfaces (H_S) is approximately 12 μSv h^{-1}; the dose equivalent due to the primary beam scattered from the patient or phantom (H_{ps}) is approximately 45 μSv h^{-1}; the dose equivalent due to the scattered head leakage photons (H_{LS}) is approximately 16 μSv h^{-1}; and the dose equivalent due to the leakage radiation which is transmitted through the inner maze wall (H_{LT}) is approximately 2 μSv h^{-1}.

Using the semiempirical calculations described in Sec. II A, the calculation results of neutron dose equivalent rate were obtained by the Kersey method, the modified Kersey method, and the Falcão method. The calculation results are listed in Table I, with their counterparts of the maximum measurement results. The maximum of measured $H_{n,D}$ and H_G were obtained using the conditions described in Sec. III A, with the gantry at 270° and the closed jaw setting. The ratios of the calculated values to the measured ones are also listed in Table I.

III.C. Dose measurement for shielding

In order to investigate the shielding effect of lining portions of the maze wall with borated polyethylene, a series of measurements were performed with one or multiple (up to six) BPE boards placed on the maze wall at locations a–l (Fig. 2). The $H_{n,D}$ and the H_G were measured using the conditions described in Sec. III A, i.e., with the gantry at 270° and the closed jaw setting. According to the single board shielding effect and comparison of different location combinations of multiple boards, we chose d–i as the optimized locations to install the six pieces of the BPE boards. Lining the inner corner of the maze at locations d–i with BPE boards provides 59% and 41% reductions for the H_G and the $H_{n,D}$, respectively, at the maze entrance (Table II). Also, a 56% reduction was achieved for both the dose equivalents at point F in the adjacent console area (Fig. 2).

TABLE II. Final measurements at the maze entrance and the control area of adjacent vault.

	Readings and reduction at entrance		Readings and reduction at console area of adjacent vault	
	Photon (μSv h^{-1})	Neutron (μSv h^{-1})	Photon (μSv h^{-1})	Neutron (μSv h^{-1})
Reading before shielding	305	925	25	45
Reading after boron shielding	125	550	11	20
Reduction	59%	41%	56%	56%

IV. DISCUSSION

IV.A. Maximum reading setup in measurements

The observations of the maximum reading setup (270° gantry angle and closed jaw setting) are consistent with the measurements by McGinley and Huffman,[28] and the Monte Carlo calculations by Ma *et al.*[29] It is more likely for a scattered neutron to escape to the maze when the gantry is at 270° as opposed to 90°. Furthermore, when the jaws are closed, the average neutron energy will decrease[25] and therefore the neutron absorption cross section may increase. This will result in a higher neutron dose equivalent and neutron capture gamma dose equivalent.

It is worth mentioning that the major component of the error bars in Fig. 3 is systematic and does not affect the relative relationship between the measurement data (of either the neutron or the photon measurement). Repeated measurements support the above observation of this trend.

IV.B. Photon dose equivalent components

IV.B.1. Components in the calculations

All five components (H_S, H_{ps}, H_{LS}, H_{LT}, and h_φ) of photon dose equivalent will contribute to the total photo dose equivalent (H_G) at the maze door when the jaws are open. According to the calculation results in Sec. III B, the H_S and the H_{ps} contribute about 19%–24% of the H_G at different gantry angles. When the jaws are closed, the H_S and the H_{ps} can be ignored and the H_{LS} and the H_{LT} contribute about 8%–10% of the H_G. Changing the gantry angle will cause a variation of 10% of the sum of the H_{LS} and the H_{LT} and only about 1% of the H_G with the close jaw setting. According to the calculations, the neutron capture gamma dose equivalent is the dominant component of the H_G, especially for closed jaws (68%–75% for the open jaw setting and 90%–92% for the closed jaw setting).

IV.B.2. Neutron capture γ-rays in measurements

(a) Open field. The neutron dose equivalent is 40% greater at the 180° gantry angle than at 90° where the gantry head is furthest away from the inner maze entrance. The neutron dose equivalent is 43% smaller when the gantry is at 270° than at the 180° gantry angle. Correspondingly, the photon dose equivalent is 5% smaller at the 90° gantry angle and 47% smaller at 270° when compared to the gantry at 180° (beam pointing down) for the maximum open field size ($40\times 40\ cm^2$). The similar trend of the curves suggests that at the maze door, the photon dose is largely affected by the neutron field and that the neutron capture γ-rays are a major component of the photon field. However, the much smaller dose increment of photons than that of neutrons from 90° to 180° gantry angle indicates that the H_G is also determined by other components of photons, such as primary beam scattering photons, when the jaws are at their maximum settings.

(b) Closed field. The increase of the photon dose equivalent with gantry angle is observed through measurements with the minimum field size ($0.5\times 0.5\ cm^2$). The trend of the curves of the $H_{n,D}$ and the H_G are close to each other. The H_G is 50% greater at 270° than at the 90° gantry angle, while the $H_{n,D}$ is 29% greater. Since the H_{LS} and H_{LT} will not change dramatically with the gantry angle according the calculation results, we assume that the large increment of the H_G (50%) is majorly caused by the neutron capture γ-rays. Although the neutron capture γ-rays component cannot be quantitatively distinguished from the leakage photons, the measurement data indicate that the neutron capture γ-rays are a major, possibly a dominant, component of the photon field at the maze door when the jaws are closed.

IV.B.3. Primary beam scattering photons in measurements

(a) Open field. All five components of the photon fields, h_φ, H_S, H_{ps}, H_{LS}, and H_{LT}, contribute to the total photon dose equivalent at the maze door. Based on the calculation results in Sec. III B, the H_{LS} and the H_{LT} were assumed to be constant when the gantry rotates. The significance of the primary beam scattering photons can be observed in the measurement data. When the gantry is at 90°, the primary beam will irradiate the west wall (Fig. 2) so that the primary beam has a higher probability of being scattered into the maze than at the 270° gantry angle. The H_G increases correspondingly. When the gantry turns from 90° to 180°, the primary beam has a lower probability to be scattered into the maze. However, the H_G increases from 260 μSv h^{-1} at 90° to 275 μSv h^{-1} at 180°. This may be due to the increase of the neutron capture γ-rays with the increasing neutrons fluence in the maze when the gantry turns from 90° to 180° (Fig. 3).

(b) Closed field. The primary beam scatter can be ignored for the closed field ($0.5\times 0.5\ cm^2$). If the primary scattering photons are dominant, the H_G for the closed field should be lower than that for the maximum open field ($40\times 40\ cm^2$). However, the H_G only has a lower value at the 90° gantry angle for the closed field. At the 180° gantry angle, the H_G for the closed field is 7% greater than that for the open field. At the 270° gantry angle, the H_G for the closed field is 107% greater than that for the open field. The measurement data suggest that the primary beam scattering photons are a major component of the total photon dose equivalent, but are not dominant.

IV.B.4. Counteractive effect of neutrons capture γ-rays and primary beam scattering photons

From the above discussions, it should be noticed that there is a counteractive effect from the neutron capture λ-rays and the primary beam scattering photons to the total photon dose equivalent. The H_G is mainly affected by the following factors: The variation of the primary beam scattering photons with the gantry angle, the variation of the neutron fluence in the maze with the gantry angle, and the variation of the neutron capture gamma production with the change of average neutron energy.

(a) Open field. The scattering of the primary photon beam at the maze door will increase when the gantry head moves away from the inner maze entrance and the primary beam is turning toward the wall near to the inner maze entrance. The neutron fluence in the maze is reflected by the nonmonotonic $H_{n,D}$ curve in Fig. 3. The trend of the H_G curve with the open jaw setting is majorly affected by these two factors, i.e., the variation of the primary beam scattering photons and the variation of the neutron fluence in the maze.

(b) Closed field. The H_G is mainly affected by the variation of the neutron fluence in the maze with the position of the gantry head with respect to the inner maze entrance. It increases as the gantry head gets closer to the inner maze entrance.

(c) From closed field to open field. The scattering of the primary photon beam at the maze door will be higher with the open field than that with the closed field. Furthermore, the jaws are one of the major sources of neutron production.[26,30] The average neutron energy will increase from 0.29 to 0.4 MeV when the jaws are open,[25] so that the neutron absorption cross section and the production of capture γ-rays may be lower. Due to the above effects, the H_G does not always decrease as much as the $H_{n,D}$ does when using the maximum open field versus the closed filed, as shown in Fig. 3. At 180° gantry angle, the H_G does not decrease significantly when using the maximum open field versus the closed field. The H_G even increases by 30% at 90° when jaws change from the closed jaw setting to the maximum open jaw setting.

IV.C. Comparison of measurement and semiempirical calculations

IV.C.1. Photon dose equivalent calculations

The calculated H_G underestimates the measured dose equivalent by 2%–23%. The calculated H_G is the sum of contributions from the primary beam scattering photons (H_S and H_{ps}), the gantry head leakage (H_{LS} and H_{LT}), and the neutron capture γ-rays (h_φ). Including all these contributions in the calculation will give the highest possible prediction of the dose equivalent at the maze door. With consideration of the measurement uncertainty, the formulae in NCRP Report No. 151, including Eq. (6) proposed by McGinley *et al.*, give a very close estimation to the H_G. However, the tendency to underestimate the H_G needs to be carefully considered in shielding calculations.

It should be noted that the maximum photon dose equivalent H_G obtained in the measurement happened with the closed jaws setting, which means the primary beam scattering component did not exist or was negligible during the measurement. However, the calculated H_G without the primary beam scattering components (H_S and H_{ps}) is only 177–241 μSv h^{-1} and is lower than the highest possible dose equivalent in the calculation, which includes all the components. There is a contradiction of the conditions to obtain the maximum H_G from the measurements and the calculations. It may partially be caused by the same K value that was used in both the h_φ calculations with the open jaw setting and the closed jaw setting. The parameter K is the ratio of the neutron capture gamma dose equivalent to the total neutron fluence. With the jaws closed, the average energy of the neutrons will decrease.[25] The neutron capture gamma production per neutron fluence will increase due to the change of the neutron absorption cross section. Therefore, using the K value for both jaw settings does not reflect the changes in the neutron average energy and the corresponding neutron capture gamma production. Before the K values for different jaw settings are available, it is recommended to include all the possible components of the photons in a treatment room shielding calculation.

IV.C.2. Neutron dose equivalent calculations

The results in Table I show that Kersey method overestimates the measured $H_{n,D}$ by a factor of 2.4–3.8. This result is consistent with the observations of Carinou *et al.*[4] and McGinley *et al.*[8] The calculated $H_{n,D}$ by the modified Kersey method underestimates the measured dose equivalent by 11%–37%. The Falcão method overestimates the $H_{n,D}$ by a factor of 3.9–5.5. With consideration of the measurement uncertainty, the measurement data are in favor of the modified Kersey method. However, it is worth noting that the modified Kersey method has the tendency to underestimate the $H_{n,D}$ and should be used with extra caution.

In the Falcão method, the $H_{n,D}$ calculation accuracy depends largely on the knowledge of the average neutron energy at the inner maze entrance. The average neutron energy could drop from about 0.5 MeV at 1 m distance from the gantry head[27] to about 20 keV in the maze[31] for accelerators working at 10–18 MV. According to Fig. 31 of the ICRP Publication 74,[21] there is a steep slope of the conversion factors in the neutron energy range from 20 keV to 0.5 MeV. The value of the conversion factor increases 19 times in this energy range. Determining on the accurate average neutron energy for different accelerators and maze designs will be a challenge for those who tend to use the Falcão method to do the semiempirical shielding calculations. Additional neutron average energy information should be available for different medical accelerators in order to apply this method accurately. However, the modified Kersey method relies on the neutron source strength Q_n, which is available for most commercial linacs, and the geometry information of the maze, which is usually known to the linac users. Therefore, the modified Kersey method may still have an important advantage in practical shielding calculations.

IV.D. Dose measurement for shielding

The similar trend of dose reduction of both the neutron and photon field supports the conclusion that neutron capture γ-rays are a major component of the photon field at maze entrance. After the shielding, the maze has a 4.39 m TVD (derived by the modified Kersey method), which is 15% shorter than the TVD before the shielding (5.15 m). The $H_{n,D}$ reduction after the shielding (41%) is close to the Monte Carlo simulation results, i.e., 65% reported by Carinou *et al.*[4] and 69% by Agosteo *et al.*[32] Agosteo *et al.* simulated standard concrete wall plus 2.5 cm BPE with 4% boron in weight, which is less than the 5% boron in the BPE used by Carinou *et al.* and our group. In the above two Monte Carlo simulations, the whole maze wall was covered with BPE boards as opposed to our study where we only lined the inner corner of the maze with BPE boards. Therefore, the higher reduction values reported by Carinou *et al.* and Agosteo *et al.* are reasonable. A similar shielding method as in our study reported by Lalonde[11] shows that using polyethylene and flexboron panels as the shielding materials can reduced the $H_{n,D}$ by 50% and the H_G by 32%, which are close to our results.

V. CONCLUSIONS

This series of measurements provides neutron and photon dose equivalent data at the maze entrance and at the adjacent treatment console area of a Varian Clinac 23EX medical accelerator operated at 18 MV photon mode. The neutron and photon dose equivalent measurement data indicate that the neutron capture γ-rays are a major and possibly a dominant component of the photon field at the maze entrance. These results also compare favorably to the modified Kersey method. The calculations of the modified Kersey method are in agreement with the measurements within 11%–37% for our maze design. However, the results show that the Kersey method overestimates the $H_{n,D}$ by 2.4–3.8 times and the Falcão method overestimates the $H_{n,D}$ by 3.9–5.5 times for our maze design. The large discrepancy of the Falcão method was partially attributed to the ICRP conversion factors based on estimations of average neutron energy. The widely used modified Kersey method is recommended for the shielding calculation of a Varian Clinac 23EX accelerator in a similar maze, with caution to its potential to underestimate the $H_{n,D}$.

Borated polyethylene is an efficient material in neutron dose reduction as well as neutron capture gamma dose reduction. After applying BPE boards as a lining material on the maze wall, the $H_{n,D}$ at the maze entrance was decreased by 41% and the H_G was decreased by 59% when compared to the unshielded measurements. The maze in this study has a TVD of 5.15 and 4.39 m before and after lining the inner corner of the maze wall with 2.5 cm (1 in) BPE boards, according to the modified Kersey method. This shielding approach can be applied to retrofitting an existing vault as a result of linear accelerator energy upgrades, especially when shielding cost is a concern.

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