■ PAPER ■

COMPUTATIONAL DETERMINATION OF NEUTRON DOSE EQUIVALENT LEVEL AT THE MAZE ENTRANCE OF A MEDICAL ACCELERATOR FACILITY

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Received November 29, 2006 / Accepted for Publication February 14, 2007

An empirical formula for the neutron dose equivalent at the maze entrance of medical accelerator treatment rooms was derived on the basis of a Monte Carlo simulation. The simulated neutron dose equivalents around the Varian medical accelerator by the MCNPX code were employed. Two cases of target rotational planes were considered: parallel and perpendicular to maze walls. Most of the maximum neutron dose equivalents at the doorway were found when the target rotational planes were parallel to maze walls and the beams were directed to the inner maze entrances. The neutron dose equivalents at the outer maze entrances were calculated for about 698 medical accelerator facilities which were generated from the geometry configurations of running treatment rooms, based on such gantry rotation that produces the maximum neutron dose at the doorway. The results calculated with the empirical formula in this study were compared with those calculated by the Kersey method for 7 operating facilities. It was found that the maximum disagreement between the calculation of this study and that of the Kersey method was a factor of 8.54 with the value calculated by the Kersey method exceeding that of this study. It was concluded that the kersey method estimated the neutron dose equivalent at the doorway computed by MCNPX more conservatively than this study technique.

Keywords : Photoneutrons, Kersey Method, Medical Accelerator Maze

1. INTRODUCTION

Most medical linear accelerator facilities are designed with a maze considering the required concrete shielding thickness primarily for high energy photons which can generate neutrons. The neutron shielding for concrete walls was not concerned since adequate concrete shielding for the photons will always be adequate for the neutrons as well. However, the neutron shielding at doors should be considered since the neutrons can reach the door by a single scatter. Therefore, the evaluation of the neutron doses at the outer maze entrances was significant in the design of the door shielding.

Three analytical methods for the calculation of the reduction in neutron dose equivalent at the maze entrance have been presented: the Kersey method [1], the French and Wells method [2] and the McCall method [3]. The Kersey method was simple but was developed from only the measurement data acquired at four facilities and is needed to be tested for a variety of maze configurations. In addition, the method only takes into consideration the wall directly facing the maze entrance (opposing wall) and not the contribution of the maze wall to the dose at the entrance.

The French and Wells and the McCall methods were based on an albedo method. Their methods are somewhat complicated in that the scattering angles and areas of the walls need to be determined. The French and Wells method is time-consuming as well because the effects of each single scattering surface visible to the maze entrance should be included. Another problem in the French and Wells method is that thermal neutrons are not included in the calculated neutron dose equivalent since it is for fast neutrons only.

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McCall et al. [4] and McGinley et al. [5] have evaluated the accuracy of the Kersey method for a variety of treatment facilities and concluded that the Kersey method overestimated the neutron dose at the door.

In all of the methods, the neutron dose equivalent at some distance from the source should be determined, which is not easily obtained. This is because the neutron doses inside accelerator rooms are not measured by active neutron detectors (^{10}B, ^{3}He proportional counter, etc.) with pile-up effects from high rates of photon flux but are measured by passive neutron detectors (activation detectors, etc.) with separate sophisticated counting equipments as Knoll [6], NCRP 79 [7] and Tosi et al. [8] have stated.

Recently, Waller et al. [9] have yielded the relationship formula to determine the neutron dose equivalent as a function of distance away from the isocenter for a medical accelerator generating 18 MV photons. However, the formula does not reflect the affection for decreased attenuation of neutrons in the case of wider maze widths and the effect for increased reduction of neutrons in the case of thicker maze walls even in the maze configurations in which the distances from the isocenter are the same.

The goal of this work was to derive the practical, easily -applicable empirical formula for the total (thermal plus fast) neutron dose equivalent at the maze entrance as a function of only maze configuration dimensions without any information on the neutron dose rate from the accelerator target. For the accelerating photon energy of the medical accelerator, 15 MeV was chosen and a maze with one bend (single leg) was worked with because medical linear accelerators operating with 15 MV photons in facilities with single-bend maze have been running commonly as megavoltage x-ray installations.

The effectiveness for the empirical formula of this work was assessed in comparison with the Kersey method and the Monte Carlo simulation by MCNPX [10]. The Kersey method was selected as an object of the comparison because of the advantage of simplicity and it has generally been used for shielding design of the door.

2. MATERIALS AND METHODS

In use of the Kersey method, the effective neutron source position is taken to be the isocenter of the accelerator and the neutron dose equivalent (H) at the entrance to maze per unit dose of photon at the isocenter is given by the equation shown below

$$H = (H_0)\,(S/S_0)\,(d_0/d_1)^2\,10^{-d_2/5}$$

Where H_o is the neutron dose equivalent at a distance d_0 from the target. Distance d_1 which is shown in Fig. 1, is the distance in meters from the isocenter to the point on the maze center line from which the isocenter is just visible. Distance d_2 is the distance from A to B of Fig. 1. S/S_0 is the ratio of the outer maze area to the inner maze entrance area. The negative exponent term results in an attenuation of the dose equivalent by a factor of 10 for every 5m of maze length.

In this work, neutron fluence and energy spectra at 1m from the target in the fully described geometry of the Varian accelerator head, which were computed by Kim et al [11], were employed for the source term of the neutron head leakage level. The neutron tracks generated by Kim et al. were written on a spherical surface of a 1m radius from the target using the SSW card in the MCNPX code. The coordinate system of the neutron tracks was transformed according to the gantry angle set to four positions such that the photon beams were directed toward the ceiling, floor and both primary walls. In addition, two cases of target rotational planes were considered, as shown in Fig. 1: (1) the target rotational plane was aligned along the line marked 1-3 of Fig. 1 (case I), and (2) the target rotational plane was aligned along the line marked 2-4 of Fig. 1 (case II). This was to determine which location of target rotational plane and which gantry angle might produce the maximum neutron dose at the doorway.

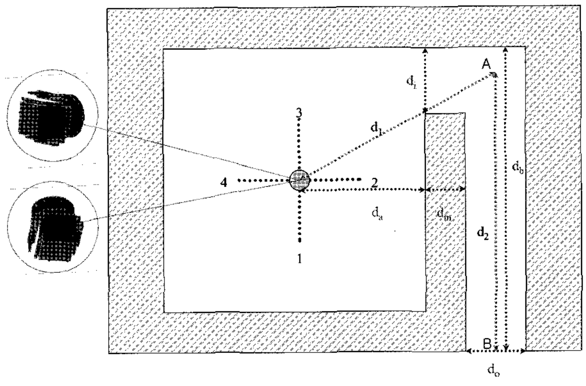


Fig. 1. Simplified schematic of treatment room and maze.

To model the maze configurations with one bend, dimension information about the following maze parameters in centimeters shown in Fig. 1 was obtained from 11 operating facilities investigated: (1) the distance from the isocenter to maze wall (d_a), (2) the distance from the maze doorway to the wall directly facing it (d_b), (3) the width of the inner maze entrance (d_i), (4) the width of the outer maze entrance (d_o), (5) the thickness of the maze wall (d_m), and (6) the height from the floor to the ceiling (d_h).

The neutron fluences around the head of the accelerator were transported toward the maze entrance by MCNPX for the cases of the 14 facilities generated by combining the maximum, minimum, average dimensions for each of the above 6 maze parameters. The simulated neutron fluences at the doorway were converted to the neutron dose equivalent using the fluence to ambient dose equivalent conversion factors from ICRP 74 [12].

Under such irradiation conditions which lead to the maximum neutron dose at the doorway, the neutron dose equivalents at the maze entrances were computed for the 698 treatment rooms which were generated by changing the dimensions at regular intervals for the above 6 maze parameters.

A multiple regression fit was performed on the neutron dose equivalents at the doorway for the 698 treatments. The empirical relationship as a function of maze parameters was yielded.

When comparisons of neutron dose equivalents at the door, evaluated by the MCNPX code and this study method, were made with those of the Kersey method, the maximum neutron dose equivalent per unit photon dose (3.49 mSv/X-Gy) at the isocenter, computed by Kim et al., was employed as the neutron dose equivalent (H_0) at 1m from the target, required in the Kersey method for consistency in source terms. For the ratio S/S_0 in the Kersey method, 1 was applied for consistency in geometry where the outer maze area is the same as the inner maze entrance area (d_i x d_h as Fig. 1).

3. RESULTS AND DISCUSSION

Table 1 shows the range of the maze parameters investigated in the operating 11 treatment rooms. The effect of the thickness of the maze wall on neutron dose equivalent at the doorway was depicted in Fig. 2 under such maze configurations where only the thickness of the maze wall was changed and the foregoing remaining 5 parameters were fixed. All data in Fig. 2 was normalized to 1 for the minimum thickness of the maze wall. The effect of the width of the inner maze entrance was shown in Fig. 3 under such maze configurations where only the width of the inner maze entrance was changed and the foregoing remaining 5 parameters were fixed. All data in Fig. 3 was normalized to 1 for the maximum width of the inner maze entrance. It was observed that the thicker the maze wall, the lower the neutron dose equivalent at the doorway is and the wider the inner maze entrance, the higher the neutron dose equivalent is. This phenomenon is due to the fact that the attenuation of neutrons from interactions with the maze wall increases as the maze wall gets thicker and the neutrons passing through the inner maze entrance without any collisions with the maze wall increase as the inner maze entrance gets wider. These effects aren't considered in the Kersey method.

Table 1. Range of the maze parameters investigated in the operating 11 treatment rooms.

Maze parameter in Fig. 1	Dimension(cm)
d_a	260 ~ 400
d_b	690 ~ 1,084
d_i	180 ~ 305
d_o	120 ~ 230
d_m	50 ~ 140
d_h	250 ~ 397

The majority of the neutron dose equivalents at the doorway in the foregoing 14 facilities were at a maximum

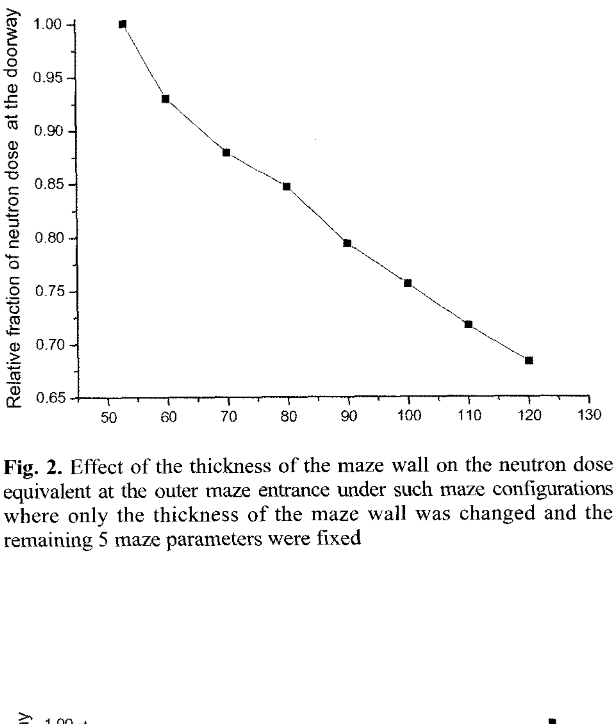


Fig. 2. Effect of the thickness of the maze wall on the neutron dose equivalent at the outer maze entrance under such maze configurations where only the thickness of the maze wall was changed and the remaining 5 maze parameters were fixed

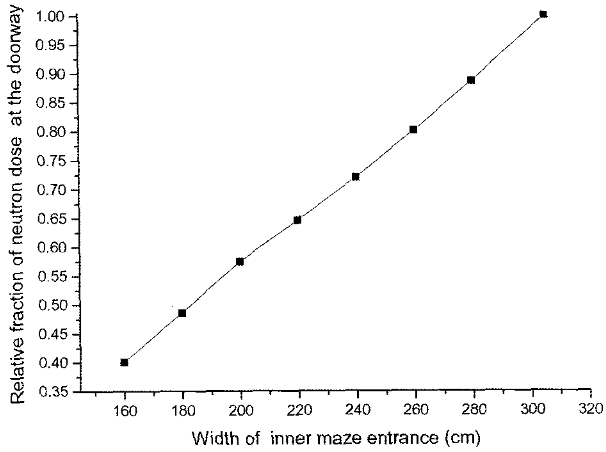


Fig. 3. Effect of the width of the inner maze entrance on the neutron dose equivalent at the outer maze entrance under such maze configurations where only the width of the inner maze entrance was changed and the remaining 5 maze parameters were fixed

Table 2. Relative neutron dose equivalent* at the doorway as a function of beam direction. Beam direction based on Fig. 1.

Facility no.	Target rotational plane of case I in Fig. 1				Target rotational plane of case II in Fig. 1			
	Beam direction				Beam direction			
	down	up	1 to 3	3 to 1	down	Up	4 to 2	2 to 4
1	0.944	0.902	1.000	0.753	0.984	0.942	0.996	0.764
2	0.956	0.911	1.000	0.76	0.917	0.876	0.905	0.739
3	0.945	0.892	1.000	0.756	1.007	0.964	1.03	0.812
4	0.971	0.9	1.000	0.765	0.929	0.902	0.92	0.78
5	0.916	0.868	1.000	0.742	1.006	0.963	0.986	0.781
6	1.027	1.045	1.000	0.877	0.897	0.869	0.855	0.803
7	1.02	0.8	1.000	0.698	1.094	0.859	0.977	0.749
8	0.934	0.923	1.000	0.765	0.988	0.939	0.994	0.781
9	0.944	0.937	1.000	0.768	0.961	0.957	1.005	0.764
10	0.963	0.935	1.000	0.804	1.049	0.97	1.017	0.811
11	0.966	0.914	1.000	0.768	1.011	0.951	1.001	0.771
12	0.929	0.892	1.000	0.737	0.959	0.925	0.973	0.756
13	0.979	0.914	1.000	0.76	0.99	0.987	0.984	0.781
14	0.964	0.893	1.000	0.76	0.987	0.938	0.994	0.772

* All data have been normalized to 1 for the gantry in the position such that the beam was directed toward point 3 and the target rotational plane was aligned along the line marked 1-3 of Fig. 1(case I)

Table 3. Comparison of neutron dose equivalents at the doorway per unit photon dose at the isocenter, evaluated by the MCNPX code and this study method, with those by the Kersey technique.

Facility no.	Neutron dose equivalent (mSv/X-Gy)			Ratio (Kersey/MCNPX)	Ratio (Kersey/this study)
	MCNPX	This study	Kersey		
1	8.52×10^{-4}	1.00×10^{-3}	6.20×10^{-3}	7.28	6.17
2	3.19×10^{-4}	4.74×10^{-4}	1.66×10^{-3}	5.21	3.50
3	2.19×10^{-4}	3.23×10^{-4}	7.99×10^{-4}	3.65	2.47
4	7.67×10^{-4}	8.69×10^{-4}	3.84×10^{-3}	5.01	4.42
5	1.06×10^{-3}	1.19×10^{-3}	1.01×10^{-2}	9.58	8.54
6	9.11×10^{-4}	1.06×10^{-3}	8.22×10^{-3}	9.02	7.72
7	3.36×10^{-4}	4.29×10^{-4}	1.39×10^{-3}	4.15	3.25

level when the gantry was rotated so that the target was at point 1 in Fig. 1 and the beam directed toward point 3 in Fig. 1, as shown in Table 2. All data in Table 2 have been normalized to 1 for the case of that gantry rotation. Table 2 shows several cases where the maximum neutron doses was observed for other gantry rotations, but the difference between the normalizing gantry rotation and other gantry rotations was very slight. From these results, it can be deduced that the maximum neutron dose equivalent is produced when the target rotational plane passes through line 1-3 of Fig. 1 and the gantry angle is set to give a horizontal beam directed from point 1 to point 3.

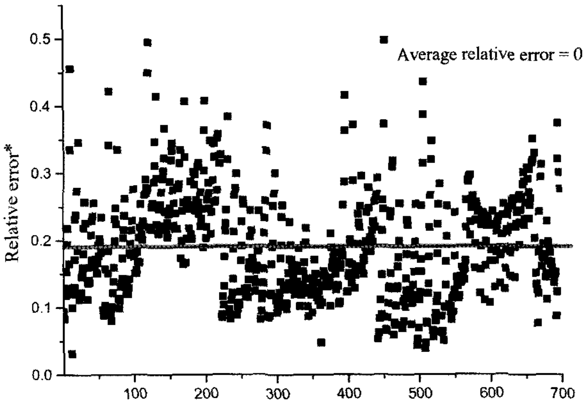
The empirical formula for neutron dose equivalent at the doorway was derived as a function of the dimensions of maze configuration as follows:

$$H = 4.969 \times \left(\frac{d_o}{d_m + d_o}\right)^{1.55} \times \left(\frac{d_c^{\,2}}{d_a^{\,2}}\right)^{0.417} \times \left(\frac{d_i \times d_h}{(d_b - 120)^2}\right)^{1.59}$$

Where, H is the neutron dose equivalent (mSv) at the doorway per unit photon dose (X-Gy) at the isocenter (mSv/X-Gy) and the 6 maze parameters (d_a, d_b, d_i, d_o, d_m, d_h) in centimeters have been defined in the previous section and d_c is a constant (a distance of 1m away from the target).

This relationship equation was based on the followings: (1) a multiple regression fit to the simulated neutron dose equivalent by MCNPX under the above worst-case irradiation conditions for the above stated 698 treatment rooms, and (2) correction for underestimation degrees of the fitted results occurred in the multiple regression fit so that the fitted value may not underestimate the corresponding neutron dose equivalent.

In Fig. 4, the results of the multiple regression fit to the neutron dose equivalents at the door in 698 treatment rooms were compared with the MCNPX simulated values by using the relative error. The relative error was formed by dividing the MCNPX simulated value into the remainder between the multiple regression results and the MCNPX simulated ones. The average relative error was within 20%.



Treatment room no.

* Relative error = (regression value - MCNPX simulated value) /MCNPX simulated value

Fig. 4. Comparisons of the regression results with the MCNPX simulated values.

The neutron dose equivalents at the door per unit photon dose at the isocenter calculated by the Kersey method were compared with those computed by MCNPX and those by this study method for the maze configurations of 7 operating treatment rooms in Table 3. The results calculated by the Kersey technique were greater than those computed by the MCNPX simulation from by a factor of 3.65 to 9.58, and greater than those evaluated by the method of this work from by a factor of 2.47 to 8.54. It was found that the difference between the three methods was minimum for facility 3 whose maze length (d_b) is long (>10 m). This is due to the fact that the negative exponent in the Kersey formula contributes to attenuation of neutrons to a high degree relatively to the other 6 maze configurations in which the maze lengths are from 7.16 m to 8.97 m.

As expected, it was observed that the Kersey method again overestimated the neutron dose at the doorway. This result agreed with the reports of McCall et al. and McGinley et al. on the point.

4. CONCLUSION

The neutron dose equivalents at the doorway for the 698 maze configurations of medical accelerator facilities with one bend maze were computed by transports of the neutron fluences and energies around the fully modeled accelerator head by means of the MCNPX code. These simulations were performed for a 15 MV photon field from the Varian high energy medical accelerator. In addition, the four gantry angles for each of two cases of the target rotational planes (parallel to, and perpendicular to the maze wall) were considered. Finally, the empirical relationship between the neutron dose equivalent at the doorway and parameters of maze configurations were produced.

The empirical formula in this work yields less conservative estimation of the neutron dose equivalent at the doorway computed by MCNPX than the Kersey method, and is applicable easily to the maze design because it is only as a function of maze parameters and albedo parameters such as a scattering angle and an area are not needed unlike French and Wells method and McCall method.

The measurements of the neutron dose equivalents at the maze entrance of various operating treatment rooms and comparisons with the calculations by the empirical formula in this work have been made to determine if that formula would be applicable to any medical accelerator regardless of manufacturers.

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