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Neutron dose distribution in the treatment room for an accelerator in the flattening filter-free mode

Dingjie Li[1] | Xiaowu Deng[2] | Ying Xue[1] | Zhaoyang Lou[1] | Yougai Zhang[1] | Wei Guo[1] | Jianhua Wang[1]

[1]The Affiliated Cancer Hospital of Zhengzhou University, Zhengzhou, China

[2]The Affiliated Cancer Hospital of Zhongshan University, Guangzhou, China

Correspondence
Wang Jianhua, The Affiliated Cancer Hospital of Zhengzhou University, Zhengzhou,450008, China. Phone: 13938278827.
Email: huajianye@sina.cn

Abstract

Objective: To provide specific data and to make recommendations for radiation protection for clinical applications, the neutron cumulative dose, and exposure time in the treatment room around an accelerator operating at 10 MV in the conditions of both a conventional dose rate (with a flattening filter [FF] mode) and an ultra-high dose rate (flattening filter-free [FFF] mode) were measured and analyzed.

Methods: In the accelerator treatment room, the data were collected from four representative sites: the therapist's operating location, the distal end of the couch in the patient plane, the proximal maze, and the protective door. The field sizes were 5 × 5 cm^2, 10 × 10 cm^2, and 30 × 30 cm^2; the output doses were 500 MU, 1000 MU, and 2000 MU; the solid water phantom simulating the patient's body was put on the isocenter; the dose rate in FF mode was a 10-MV X-ray at 600 MU/min; and the dose rate in FFF mode was 2400 MU/min. Under the same conditions, data were collected outside the selected area measuring three positions: the protective door, operating room, and center of the main protective wall position.

Results: The neutron cumulative dose was negatively correlated with the field size; the closer to the target, the larger the neutron cumulative dose. The neutron cumulative dose was the largest at the distal end of the couch, and the neutron cumulative dose in FF mode was almost threefold as large as that in FFF mode. The neutron exposure time was positively correlated with the output dose. The FF mode takes slightly longer than the FFF mode. No neutron dose was read outside the accelerator room.

Conclusions: Operating the accelerator in FFF mode will benefit both the patients and radiation therapists by reducing the neutron cumulative dose and exposure time. The current anti-neutron accelerator room design is equally applicable to an ultra-high-dose rate (FFF) mode accelerator.

KEYWORDS
10-MV X-ray, flattening filter-free, neutron, radiation protection

1 | INTRODUCTION

Intensity-modulated radiation therapy has greatly improved the quality of radiotherapy, and it does not rely on a very uniform beam distribution. However, compared with conformal radiotherapy technology, intensity-modulated radiation therapy has increased the output dose and treatment time. This is because intensity-modulated radiation therapy is achieved by a large number of small fields that are formed by the multileaf collimator (MLC), so that the extension of the exposure time will bring many negative factors, such as a smaller number of patients per unit treatment time, an increase in target movements during the treatment, and an increase in machine losses.[1–3] The

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flattening filter-free (FFF) mode arises at a historic moment, and can maintain plan quality under the premise of reducing the irradiation time.

There are two dose rate modes of the Varian Truebeam accelerator: the conventional dose rate mode (with the flattening filter [FF] mode) and the ultra-high dose rate mode (FFF mode). Compared with the traditional accelerator, the changes in the beam intensity distribution and dose characteristics in the phantom will lead to changes in the neutron and induced ray distributions. Some studies have focused on the percentage depth dose, off-axis ratio, penumbra, collimator leak,[1] MLC leak,[2] and radiotherapy planning. It is considered that FFF technology can satisfy the need for radiotherapy patient radiological protection, meet quality assurance requirements, improve the treatment effect, and greatly reduce the irradiation time. Despite the great effort that has been made in FFF technology, detailed information on FFF technology in terms of its clinical advantages is still lacking. The present study focuses on the neutron cumulative dose and duration of the FF technology. At present, tumor patients are treated by high-energy X-rays, and the useless neutron irradiation is harmful to patients and technicians. Focusing on the durations of the different positions of neutrons in the two models will help the technician carry out a reasonable operation process arrangement to reduce or eliminate the neutron irradiation.

2 | METHODS

2.1 | Accelerator

The TrueBeam is a linear accelerator manufactured by Varian (Varian Medical Systems, Palo Alto, CA, USA) that has four modes, 6 MV, 10 MV, 6 FFF MV, and 10 FFF MV, for the X-ray energy. The highest dose rate for the 6-MV and 10-MV modes is 600 MU/min, 1400 MU/min for the 6-FFF MV mode, and 2400 MU/min for the 10-FFF MV mode; 6 MeV, 9 MeV, 12 MeV, 15 MeV, 18 MeV, and 20 MeV are built-in values for the electron beam.

2.2 | Structure and shielding thickness of the treatment room

All the treatment rooms are on the second floor underground, and lie on either of the main protective walls. Two adjacent treatment rooms share the main protective wall. The control room lies outside of the maze. All protective walls were made of poured concrete with a density of 2.35 g/cm^3. Air circulation is set at 10 times/h.

2.3 | Measuring devices

A 190-1N ion chamber survey meter that was manufactured by FLUKE Fluke International Corporation, Washington, D.C., USA was used. The neutron dose–response factor is 0.939, the calibration factor is 1.07, the measuring range is 0.1 μSv/h–10000 μSv/h, and the device is used in the period of validity.

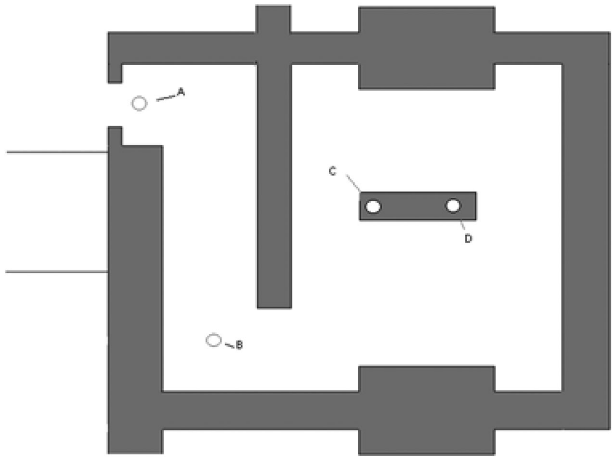

FIGURE 1 Top view of the measuring point in the treatment room (A, protective door; B, proximal maze; C, distal end of the couch in the patient plane; D, therapist's operating location)

2.4 | Items and methods

2.4.1 | Items

The neutron cumulative dose and exposure time at 10 MV in both FF mode and FFF mode were measured twice each. The dose rate of the FF mode was 10-MV X-ray 600 MU/min, and the dose rate of the FFF mode was 2400 MU/min. In the two modes, the data were shown to vary with the field size, dose rate, and measuring site. As is shown in Figure 1, the data were collected at four representative sites: the therapist's operating location, the distal end of the couch in the patient plane, the proximal maze, and the protective door. The field size was 5 × 5 cm^2, 10 × 10 cm^2, and 30 × 30 cm^2, the output doses were 500 MU, 1000 MU, and 2000 MU, and the solid water phantom simulating the patient's body was put on the isocenter.

2.4.2 | Measuring methods

A 30-cm × 30-cm × 30-cm block of solid water was used to mimic the body, with the SSD set at 100 cm. Cumulative mode was used for the survey meter when the neutron cumulative dose was tested. The neutron exposure time refers to the time when the beam is out until the survey meter shows no reading. Ratio mode was used for the exposure time test. Both items were tested for the beam out twice under the same conditions. During the beam out, videos were recorded to obtain the cumulative dose and exposure time. Considering the accelerator repeatability error, each item was measured five times, and all the measurements of the accelerator gantry angle were zero. Additionally, in the same conditions, the data were collected outside the selected area measuring three positions: the protective door, operating room, and center of the main protective wall position.

2.5 | Statistical analysis

The SPSS 17.0 package SPSS Inc., an IBM Company Headquarters,Chicago, USA was used to carry out the multifactor analysis and

TABLE 1 Neutron cumulative dose (μSv)

field size(cm^2)										
Dose (MU)		5 × 5			10 × 10			30 × 30		
Mode	Position	500	1000	2000	500	1000	2000	500	1000	2000
10 FFF	Protective door	0.0.05 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.08 ± 0.0	0.1 ± 0.0
	Proximal maze	10.1 ± 0.5	20.7 ± 0.4	40.1 ± 0.5	8.4 ± 3.8	20.1 ± 0.5	40.7 ± 1.1	19.9 ± 0.7	40.04 ± 0.3	80.0 ± 1.2
	Therapist's operating location	43.2 ± 0.6	85.6 ± 1.2	172.3 ± 1.8	32.4 ± 0.6	64.1 ± 1.2	127.5 ± 1.5	15.3 ± 0.7	30.6 ± 0.6	61.7 ± 0.7
	Distal end of the couch	51.2 ± 1.0	105.2 ± 1.2	209.2 ± 0.8	43.2 ± 0.7	86.1 ± 0.8	172.4 ± 1.7	28.4 ± 0.9	55.8 ± 1.5	111.4 ± 1.4
10 FF	Protective door	0.08 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.1 ± 0.01	0.1 ± 0.0	0.23 ± 0.0
	Proximal maze	15.54 ± 0.5	30.6 ± 0.7	60.8 ± 0.4	14.2 ± 0.3	28.5 ± 0.5	57.6 ± 0.6	70.8 ± 0.58	141.8 ± 1.1	228.2 ± 1.9
	Therapist's operating location	115.4 ± 1.1	307.7 ± 2.5	615.5 ± 3.1	134.4 ± 1.1	266.5 ± 1.0	537.4 ± 1.8	63.9 ± 1.19	128.3 ± 4.2	252.0 ± 1.5
	Distal end of the couch	163.2 ± 2.0	323.9 ± 3.1	645.1 ± 1.8	142.5 ± 1.6	282.3 ± 1.9	565.8 ± 1.7	93.2 ± 1.68	186.2 ± 0.9	374.2 ± 2.5

FF, flattening filter mode; FFF, flattening filter-free mode.

TABLE 2 Factors that affect the neutron cumulative dose (μSv)

	Group	Mean ± standard error	P^a			P^b
Output dose (MU)	500	44.41 ± 49.49	——			<0.01
	1000	91.87 ± 103.97	<0.01	——		
	2000	181.40 ± 207.26	<0.01	<0.01		
Field size (cm^2)	5 × 5	125.69 ± 178.56	——			<0.01
	10 × 10	109.38 ± 155.82	<0.01	——		
	30 × 30	82.61 ± 94.10	<0.01	<0.01		
Dose rate	10 FFF	49.36 ± 53.67	——			<0.01
	10 FF	162.43 ± 185.88	<0.01			
Position	Protective door	0.13 ± 0.08	——			<0.01
	Proximal maze	51.57 ± 53.64	<0.01	——		
	Distal end of the couch	202.2 ± 172.27	<0.01	<0.01	——	
	Therapist's operating location	105.89 ± 137.88	<0.01	<0.01	<0.01	

[a]Compared with the reference group.
[b]Compared between groups. FF, flattening filter mode; FFF, flattening filter-free mode.

linear regression analysis for the neutron cumulative dose and exposure time. $P < 0.05$ was considered significant, and a bilateral test was used.

3 | RESULTS

There were no readings of the three measurements outside of the treatment room, and the measurements inside the treatment room are shown in Table 1.

3.1 | Neutron cumulative dose

As is shown in the multifactor analysis, the output dose, beam size, dose rate, and measurement position affected the neutron cumulative dose (Table 2). As is shown in the linear regression analysis (Table 6), the neutron cumulative dose was proportional to the output dose ($P < 0.01$), and inversely proportional to the field size ($P < 0.01$). At the same condition, the neutron cumulative dose differed with the dose rate; the neutron cumulative dose was higher in FF mode than in FFF mode ($P < 0.01$). The neutron cumulative dose was higher when the measurement position was closer to the target. The neutron cumulative doses of the protective door, the proximal maze, the distal end of the couch in the patient plane, and the therapist's operating location increased in turn. The factors that affected the neutron cumulative dose are shown in Table 5.

3.2 | Neutron exposure time

As is shown in the multifactor analysis, the output dose, beam size, dose rate and measurement position affected the neutron exposure time (shown in Table 4). As is shown in linear regression analysis (shown in Table 6), the neutron exposure time increased with the output dose ($P < 0.01$) at the same condition; the neutron exposure time of the FF mode was longer than that of the FFF mode ($P < 0.01$). The neutron exposure time of the protective door, the proximal maze, the distal end of the couch in the patient plane, and the therapist's operating location increased in turn. The factors that affected the neutron exposure time are shown in Table 5.

4 | DISCUSSION

Neutrons can be produced by high-energy X rays with energies greater than 8 MV through an electron-neutron reaction or neutron-photon reaction.[4,5] Because of the higher radiation quality factor of neutron rays than that of X-rays and γ-rays, neutron radiation does more damage to the human body. Thus, neutron protection must be considered for these high-energy accelerators. Generally, there are two types of neutron in the treatment room. One is the so-called leak neutrons that accompany the main beam, and go through the target, filter, collimator, and MLC before reaching the treatment room.[6,7] The other is scattered neutrons, which are formed by the lead neutrons scattered once or more on the protective walls or other objects. Additionally, when the X-rays are exposed to the air, the body or other solids are greater than the threshold energy of the irradiated material (γ, n), and it is possible to produce neutrons; these are called scattered neutrons. Based on this theory, the main neutrons at the operating location and distal end of the couch are leak neutrons, and at the proximal maze and protective door, the main neutron radiation is contributed by scattered neutrons.

Considering the treatment plane, the measuring position chosen in the present study lies at the height of the isocenter. Four locations were selected; that is, the therapist's operating location, the distal end of the couch in the patient plane, the proximal maze, and the protective door, which represent the patient's position or the position at which the therapists generally stand. As is shown in the present study, the four aforementioned positions and the neutron cumulative dose decrease with the increase in field size. Mao *et al.*[8] and Lalonde[9] measured the neutron cumulative dose at the collimator and protective

TABLE 3 Neutron exposure time (s)

Field size(cm^2)										
Dose(MU)		5 × 5			10 × 10			30 × 30		
Mode	Position	500	1000	2000	500	1000	2000	500	1000	2000
10 FFF	Therapist's operating location	50.0 ± 0.7	54.0 ± 0.7	55.0 ± 0.7	54.0 ± 0.7	53.6 ± 0.8	54.0 ± 0.7	50.0 ± 0.7	50.0 ± 0.7	52.2 ± 0.8
	Distal end of the couch	49.2 ± 0.8	49.8 ± 0.8	50.2 ± 0.8	54.2 ± 0.8	52.2 ± 0.8	54.8 ± 0.8	49.8 ± 0.8	53.0 ± 0.7	49.8 ± 0.8
	Proximal maze	51.8 ± 0.8	49.4 ± 1.1	54.8 ± 0.8	52.2 ± 0.8	53.8 ± 0.8	49.2 ± 0.8	33.2 ± 0.8	35.0 ± 0.7	31.2 ± 0.8
	Protective door	36.0 ± 0.7	40.0 ± 0.7	38.2 ± 1.3	35.8 ± 0.8	41.4 ± 1.1	42.8 ± 0.8	35.0 ± 0.7	36.2 ± 0.8	36.8 ± 0.8
10 FF	Therapist's operating location	51.4 ± 1.5	55.0 ± 0.7	52.0 ± 0.7	51.0 ± 0.7	49.6 ± 0.9	50.0 ± 0.7	50.0 ± 0.7	52.0 ± 0.7	52.6 ± 1.1
	Distal end of the couch	49.0 ± 0.7	50.0 ± 0.7	50.0 ± 0.7	53.0 ± 0.7	53.0 ± 0.7	50.8 ± 1.1	50.0 ± 0.7	50.4 ± 0.7	53.8 ± 0.8
	Proximal maze	35.6 ± 1.1	37.8 ± 0.8	37.0 ± 0.7	37.0 ± 0.7	38.2 ± 0.8	37.1 ± 1.1	27.8 ± 0.8	38.0 ± 0.7	37.8 ± 0.8
	Protective door	32.8 ± 0.8	33.0 ± 0.7	32.2 ± 0.8	32.0 ± 0.7	35.0 ± 0.7	35.8 ± 0.8	30.0 ± 0.7	32.4 ± 0.9	33.4 ± 1.1

FF, flattening filter mode; FFF, flattening filter-free mode.

TABLE 4 Factors that affect the neutron exposure time

	Group	P^a			P^b
Output dose (MU)	500	——			<0.01
	1000	<0.01	——		
	2000	<0.01	<0.01		
Field size (cm^2)	5 × 5	——			<0.01
	10 × 10	<0.01			
	30 × 30	<0.01	<0.01		
Dose rate	10 FFF	——			<0.01
	10 FF	<0.01			
Position	Therapist's operating location	——			<0.01
	Distal end of the couch	<0.01	——		
	Proximal maze	<0.01	<0.01	——	
	Protective door	<0.01	<0.01	<0.01	

[a]Compared with the reference group.
[b]Compared between groups. FF, flattening filter mode; FFF, flattening filter-free mode.

TABLE 5 Co-actions between the factors that affect the neutron cumulative dose and exposure time

	P	
Co-action	Cumulative dose	Exposure time
Output dose and field size	<0.01	<0.01
Output dose and dose rate mode	<0.01	<0.01
Output dose and position	<0.01	<0.01
Field size and dose rate mode	<0.01	<0.01
Field size and position	<0.01	<0.01
Dose rate mode and position	<0.01	<0.01
Output dose, field size, and dose rate mode	<0.01	<0.01
Output dose, field size, and position	<0.01	<0.01
Output dose, dose rate mode, and position	<0.01	<0.01
Field size, dose rate mode, and position	<0.01	<0.01
Output dose, field size, dose rate mode, and position	<0.01	<0.01

door, and similar results were found. They claimed that the decrease in the interaction area between the high-energy X-rays and the collimator leads to a lower neutron cumulative dose. In the present study, this characteristic was also maintained when the filter was removed. The neutron cumulative dose increased with the output dose. The shorter the distance to the target center, the greater the neutron dose is.

After analyzing the data in Tables 2 and 3, the 10-MV X-ray treatment using the FFF mode can significantly reduce the dose of neutrons. First, the filter being removed from the beam line can lead to a decrease in the leak neutron dose. Second, compared with the FF mode, the decrease in photons irradiated to the patient and the decrease in the irradiation time result in the decrease of neutrons. The data of the present study showed that in the patient's treatment plane at the position of the isocenter and at the distal end of the couch, at the same treatment condition, the FFF mode can reduce the average neutron dose by a factor of approximately 3.5, and up to a maximum of 4. The neutron irradiation dose of the patient accordingly decreases by a factor of at least 3.5; similar results, with a factor of 3.7, were reported by Kry.[10] As shown in another work by Kry[11], the neutron irradiation

TABLE 6 Relationships between factors that affect the neutron cumulative dose and exposure time

	Cumulative dose		Exposure time	
Impact factor	b	P	b	P
Output dose	0.09	<0.01	0.063	<0.01
Field size	−0.04	<0.01	−0.003	0.36
Dose rate mode[a]	−113.07	<0.01	−83.26	<0.01
Position[b]	72.43	<0.01	5.56	<0.01

[a]In regression equation: flattening filter mode = 1, flattening filter-free mode = 2.
[b]In regression equation: protective door = 1,proximal maze = 2, therapist's operating location = 4, distal end of the couch = 3.

dose would be decreased by 69% if using the FFF mode during the treatment. The significant reduction of the neutron dose can reduce the risk of secondary malignant neoplasms. Some studies focused on secondary malignant neoplasms of prostate cancer caused by high-energy X-rays, and concluded that the maximum risk is estimated to be 5.1%, with 2.9% caused by neutrons.[12] The therapists also benefit from a reduction in the neutron dose, because the treatment room is activated by thermal neutrons. The thermalization materials or thermal neutron absorption of the FF and FFF modes in the treatment room have different effects on the activation flux correlation, and a 69% neutron reduction thus means more than a 69% reduction in the activation of the treatment period. Although the activator that therapists accept heavily relies on the QA program and therapist behavior, the reduced activator of the treatment room by the FFF mode will also reduce the dose received by the therapists.[13] In addition, accurately grasping the exposure time of neutrons is helpful for the staff to take radiation protection measures, such as different time intervals and energy interval, to meet the principle of radiation protection.

The neutron exposure time was positively correlated with the neutron cumulative dose; therefore, the relationships between the neutron exposure time and output dose, field size, measurement position, and dose rate mode are consistent with the neutron cumulative dose. Comparing the two models, the neutron exposure time of the FFF mode is significantly lower than that of the FF mode. The reason should be that the time of the output dose is different; for the same dose, the FFF mode is one-quarter that of the FF mode. Under the same conditions, the neutron cumulative dose of the FFF mode is lower than that of the FF mode.

Therefore, the use of the FFF mode can significantly reduce the treatment time, as well as the neutron exposure doses of the patient and therapists. Furthermore, the treatment room for the protection of the design and installation of the FF accelerator does not require any changes to meet the protection requirements for the FFF accelerator.

CONFLICT OF INTEREST

The authors declare that they had read the article and there was no competing interests.

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