Paper

Evaluation of Radiation Shielding Requirements and Self-shielding Characteristics for a Novel Radiosurgery System

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Abstract—In order to provide safe operating conditions for radiation workers and the public at large, the radiation shielding for radiotherapy treatment rooms will have to be determined by an expert physicist according to the applicable radiation control regulations. A new radiosurgery system with integrated self-shielding, called the Zap-X, obviates the need for costly and complex radiation bunkers. Radiation levels in the vicinity of the ZAP-X radiosurgery system were acquired for a number of different operating conditions, and a 3D radiation dose distribution was measured for better visualization of hot spots and the general dose distribution. The radiation shielding requirements were evaluated according to the International and Chinese standards, respectively. While the integral self-shielding of the Zap-X was designed in accordance with international standards, it was found to be insufficient for Chinese standards. In order to meet the needs of the growing new generation of radiotherapy equipment, several suggestions for improvement of Chinese standards are proposed. Health Phys. 121(5):506–512; 2021

Key words: radiation protection; radiation, medical; safety standards; shielding

INTRODUCTION

As a consequence of the rapid economic developments in China, the field of radiotherapy has in recent years experienced exponential growth. Advanced, modern radiotherapy equipment, such as the GammaKnife and proton accelerators, have become commonplace in the treatment of cancer. Due to the inherent hazards of radiation production near humans, hospitals and radiotherapy facilities have to adhere to local radiation regulations and are required to protect personnel and the public by providing appropriate shielding and protection.

A new radiosurgery system with integral self-shielding, the Zap-X, developed and manufactured by ZAP Surgical Systems, Inc., of San Carlos, CA, obviates the need for costly and complex radiation bunkers. This device is intended for stereotactic radiosurgery (SRS) treatment of benign and malignant intracranial and cervical spine lesions in the upper neck. A 3.0 megavolt (MV) S-band linear accelerator (LINAC) is the source of therapeutic radiation (Weidlich et al. 2017). Accurate therapeutic beam positioning is accomplished through independent rotations of the shielding shells that move similar to a gyroscope and support the accelerator, while a patient table is used to position the patient under the beam. The collimator is fixed to the rotating shells and itself does not rotate for beam positioning. The system is designed to provide all necessary shielding for a given typical patient workload. Therefore, additional room shielding is not needed but could be added for extremely high patient workload.

In 2020, the ZAP-X platform was commissioned and used for clinical stereotactic radiosurgery (SRS) treatments at the People's Liberation Army General Hospital 301 (PLAGH 301) in Beijing, China (Fig. 1). In order to evaluate the self-shielding characteristics, radiation exposure rate measurements were performed at a series of stations around the periphery of the device.

MATERIALS AND METHODS

Zap-X system

Radiation is generated via the Bremsstrahlung effect from an x-ray target of a 3.0-MV S-band linear accelerator (LINAC). The LINAC is mounted within a combination of yoked gimbals, and the mechanical construct enables radiation beam crossfire from 2π steradians of solid angle, as is required for conformal cranial irradiation. Akin to a large gyroscope, the LINAC rotates accurately around a common
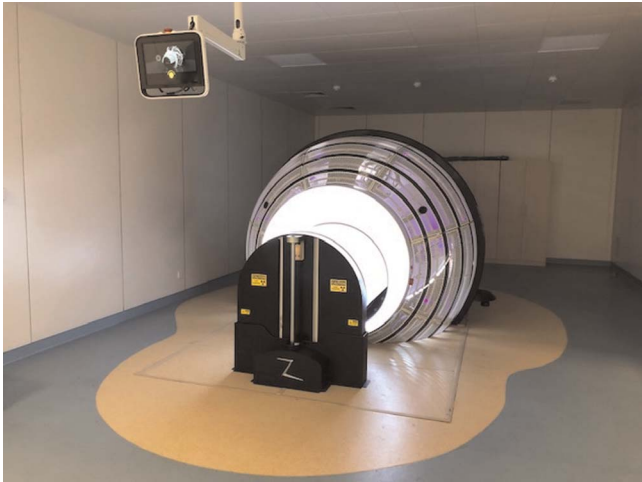
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Fig. 1. The Zap-X system installed at PLAGH 301.

isocenter. Therapeutic positioning is accomplished through dual-axes independent rotations of the accelerator and movements of a patient table. The patient and table are fully enclosed by additional shielding, which consists of a cylindrical shell and a vertical door that is designed to minimize the scatter radiation to an acceptable level. The patient's head is positioned and immobilized, while the torso and lower part of the body will extend outside the rotating iron sphere and is shielded itself by additional steel (Weidlich et al. 2017).

Most components needed to produce the beam, such as the radiofrequency power source, waveguiding system, and beam triggering electronics, as well as significant radiation shielding, are mounted on or integrated into the rotating patient treatment sphere. The patient is supported on the treatment table that extends outside the treatment sphere and is enclosed by additional radiation shielding consisting of a rotary shell and pneumatic door on a steel frame. The Zap-X accomplishes precise three-dimensional (3D) patient registration by means of an integrated planar kilovolt (kV) imaging system that also rotates around the patient's head. Non-coaxial x-ray images and image-to-image correlation are used to determine the location of the patient's anatomy with respect to the machine isocenter both prior to and during radiosurgical treatment.

For the design of the system and its shielding, primary, leakage, and scatter radiation were considered. Shielding materials used with the Zap-X are composed principally of ductile iron (specific density is 7.86 g cm^{-3}) or steel; where required, supplemental high Z materials consisting of lead or tungsten alloys were employed. Self-shielding of the ZAP-X is provided by two independently rotating iron shells as well as a cylindrical shell and vertical door that enclose the patient fully with 11-cm to 26-cm-thick iron shields. This shield provides protection from primary as well as scatter and x-ray target leakage radiation. Prior knowledge was applied to determine the material, thickness, and location of the shielding material. Fig. 2a shows the cross section of the Zap-X system, and Fig. 2b shows the room's eye-view of the Zap-X system.

Zap-X radiation leakage measurements

The dose rates of the radiation field in the vicinity of the Zap-X system were measured with an FJ1200 Radiation Survey Dosimeter that was calibrated with a secondary standard radiation source at the China Institute for Radiation Protection (CIRP). The range of the dose rate is from 0.01 to 200 μSv h^{-1} for photons. For a number of different gantry positions, radiation leakage was measured at various locations along the Zap-X boundary that is defined at 1 m from the perimeter of the system. This boundary is marked on the treatment room floor and is actively monitored by Zap-X with a laser scanner proximity detector to restrict access. The kV imaging dose is more than 6 orders of magnitude smaller compared to the therapeutic dose with much smaller energy of 75 keV, so kV imaging dose is not considered in the paper.

Measurement at major survey stations

Measurements were performed on a properly adjusted ZAP-X system at a nominal dose rate of 1,500 MU min^{-1}. An anthropomorphic head phantom placed at isocenter was used to mimic patient scatter (Weidlich et al. 2019).

The different gantry positions used for measurement are described in Table 1 and Fig. 3. The diameter of collimator of 0 and 25 mm represent the best and worst case, respectively.
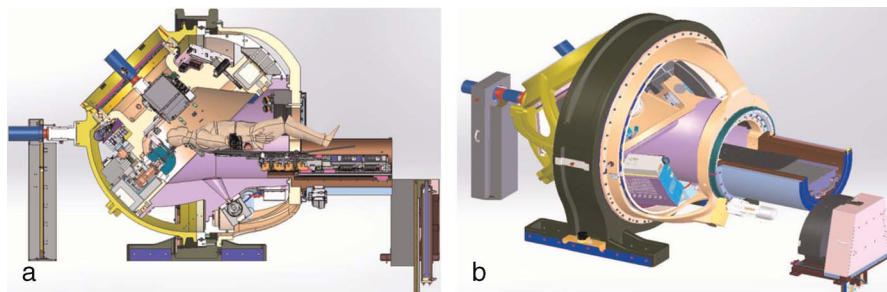

Fig. 2. Scheme of Zap-X system (Weidlich et al. 2017): (a) cross-sectional view, (b) room's eye-view.

Table 1. The different gantry positions for dose rate measurement.

No.	Gantry position	FS[a]	Phantom
A	Home position (appr. 45 deg off vertical)	0 mm	no phantom
B	Home position	25 mm	head phantom
C	Frontal position (pointing straight down)	25 mm	head phantom
D	Gantry 90° (pointing right)	25 mm	head phantom
E	Gantry 270° (pointing left)	25 mm	head phantom
F	Gantry angle 180° (pointing up)	25 mm	head phantom

[a]FS: Field size, the diameter of collimator.

Radiation at 15 stations was measured for every gantry position (A to F). The measurement stations are shown in Fig. 4 with a distance of 30 cm from the Zap-X boundary. Three separate dose rate readings were acquired at each of the 15 stations, and their average was recorded. For each station, measurements were taken at 1 and 1.5 m, respectively, above floor level to mimic the positions of gonads and thyroid of the human body. Additionally, the maximum dose rate between these two heights was determined.

Measurement of 3D radiation map

In order to evaluate the self-shielding characteristics of the Zap-X system, a 3D radiation map was generated with 855 measurement points placed equidistantly. The 3D dose distribution is graphically presented by assigning specific colors to the measured dose levels. The 3D radiation field distribution was acquired with a specialized radiation dose rate monitor, which was developed by CIRP (Fig. 5) (Zhao 2019).

With the Zap-X gantry at home position, FS = 25 mm, and head phantom at isocenter (i.e., survey case B) for each measurement point, its position was determined by use of the distance and direction to the reference station. Combining all measurement points as they were acquired at the individual locations will yield a 3D dose distribution.

RESULTS AND DISCUSSION

Radiation leakage measurements along the Zap-X boundary

Table 2 shows the dose rate (μSv h^{-1}) measured at each of the survey stations. The measurement results showed that the dose rate of the control console is the lowest for every gantry position. In addition, the exposure on the top of the sphere at 30 cm distance from the top, with an average of 19 μSv h^{-1}, was measured to evaluate the exposure of the room above.

Three-dimensional radiation field

The 3D dose distribution was calculated and displayed with color-coded radiation levels. For each measurement station, its position was determined independently (Zhao 2019). Great care was applied to overcome the difficulties in associating all measurements in 3D coordinate space. Unlike the conventional survey with 15 discreet measurement points,
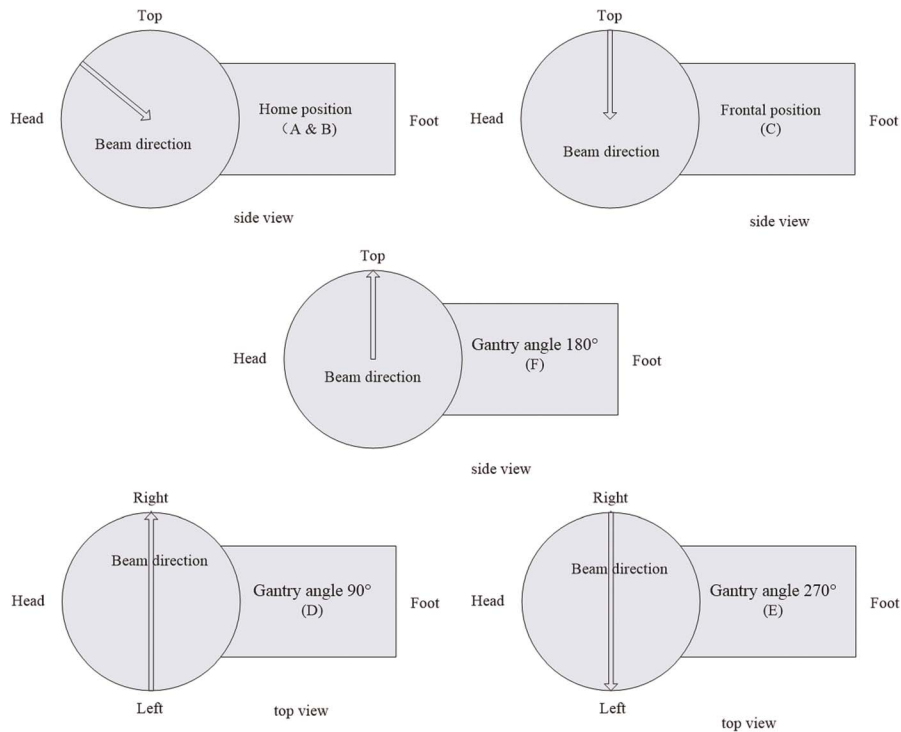
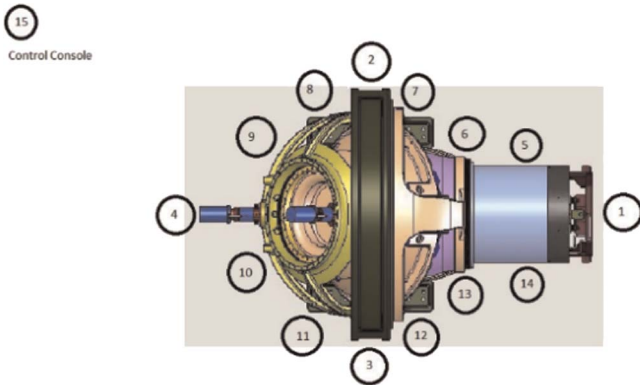**Fig. 3.** Scheme of gantry position for Zap-X system.

Fig. 4. Measurement points around the perimeter of the system.

many more points were measured for the 3D dose simulation. In areas of high dose rate and large dose rate gradient, the density of measurement points was increased. The position of Zap-X is determined by laser positioning and superimposed on the 3D map of the measurement points. The data are matched with the 3D model of the equipment, and the distribution of the entire radiation field is calculated by an interpolation method. Fig. 6a shows the 3D radiation field distribution with the different colors indicating level of radiation. Fig. 6b is the 2D projection of the 3D radiation field on the plane at the height of 79.04 cm from the floor level, which is the height of the Zap-X isocenter.

Evaluation of accumulated dose

With the development of radiotherapy, the system of international radiation protection standards was established. The International Basic Safety Standards (BSS) are the international benchmarks for radiation safety, which are used in many countries as the basis for national legislation to protect workers, patients, the public, and the environment from the risks of ionizing radiation.

In China, the standard GB18871-2002 is the basic standard for protection against ionizing radiation (MHPRC 2002). The Chinese standards defining the radiological protection requirements of electron accelerators include GBZ 126-2011, GBZ/T 201.1-2007 and GBZ/T 201.2-2011 (MHPRC 2011a and b, 2007). The GBZ 126-2011 provides the mandatory requirements of radiation shielding for the control room and the outer surface of the wall of the treatment room (MHPRC 2011b). The GBZ/T 201.1-2007 and GBZ/T 201.2-2011 are recommended, which provide the reference dose limit for radiation shielding requirements and the method of dose assessment for radiation shielding (MHPRC 2011a, 2007). In general, GBZ/T 201.1-2007 and GBZ/T 201.2-2011 are used to design the radiotherapy room and to assess the radiation dose. GBZ 126-2011 is used to evaluate the effectiveness of the radiotherapy room shielding for the electron accelerator, which requires that the ambient equivalent dose rate in the control room and the 30 cm outside the wall of the accelerator radiotherapy

room should not be greater than 2.5 μSv h^{-1}. In 2020, the new radiation protection standard for electron accelerator (GBZ 121-2020) was published to replace GBZ 126-2011 (NHCPRC 2020). In GBZ 121-2020, the instantaneous dose rate may still be used as the control level of the dose rate, but the highest reference control level of the dose rate was determined according to the different occupancy factor of the focus points. In this paper, self-shielding of the Zap-X system was evaluated according to GBZ 121-2020 (NHCPRC 2020).

The following comparison between the International standards (American and European standards) and Chinese standards are for the acceptable dose limits for the general public.

Radiation dose assessed according to international standards. In general, the goal of radiation self-shielding design of ZAP-X was determined according to the US Nuclear Regulatory Commission (NRC)'s radiation protection regulations that the total effective dose to individual members of the public from the licensed operation does not exceed 1 mSv in a year.

For ALARA purposes, the designed maximum number of a fully-booked SRS operation would be 9 treatments per day and, therefore, 2,250 treatments per year. The total
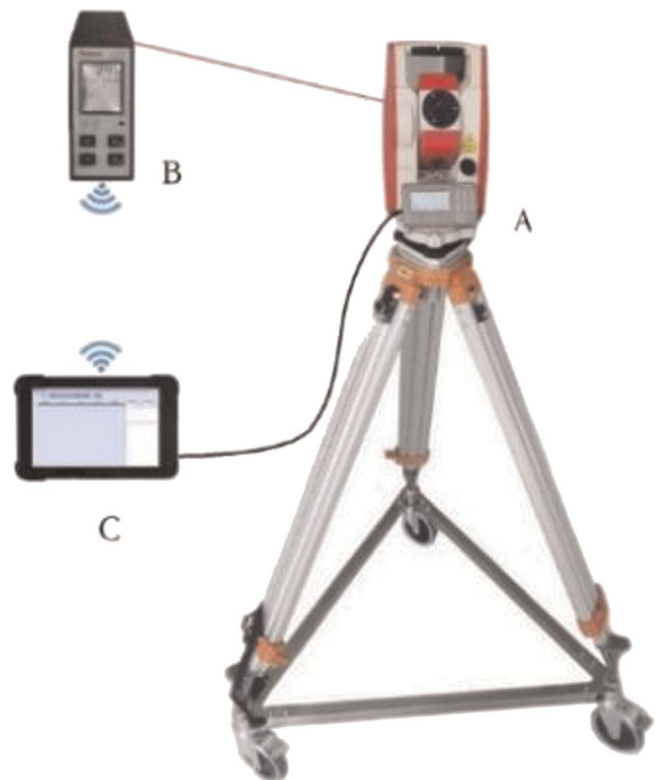

Fig. 5. Reference station and dose rate meter used for radiation field measurement: (a) reference station, (b) radiation dose meter, (c) computer.

Table 2. Measured dose rate (μSv h^{-1}) at each station for different situation (A–F).

No.	Survey stations	A		B		C		D		E		F	
		1 m	1.5 m	1 m	1.5 m	1 m	1.5 m	1 m	1.5 m	1 m	1.5 m	1 m	1.5 m
1	Foot End Table Shield	3.6	10.8	6.1	25.3	2.18	5.7	3.5	14	3.5	12.4	1.42	1.8
2	Right Side Main Gantry	1.48	1.31	1.89	1.55	1.12	1.38	1.03	1.01	2.65	2.38	0.92	1.28
3	Left Side Main Gantry	1.34	1.07	1.31	1.19	1.41	1.2	1.11	2.03	1.08	1.3	1.47	1.21
4	Head End of System	17.7	6.8	17.3	12.8	7.2	6.1	14.4	5.4	1.67	2.07	1.27	2.7
5	Table Right	1.65	1.65	1.7	1.83	1.32	1.94	3.6	5.6	1.4	1.38	1.85	1.46
6	Table-Orbit Right	1.4	1.47	1.68	1.88	1.89	3.2	6.6	5.8	1.71	1.52	1.56	3.8
7	Right Gantry	0.76	1.15	0.98	1.11	2.69	4.5	5.2	4.3	2.6	1.37	1.78	6.4
8	Right Gantry	7.2	8.4	8.2	9.4	2.26	1.68	2.03	1.57	7.9	13.4	2.21	2.5
9	Right – Head	11.9	14.8	12.2	14.5	6.2	5.6	1.87	1.53	14.3	14.2	2.11	2.5
10	Left – Head	16.4	18.1	18.3	18.5	2.41	2.39	13.8	11.6	1.15	1.16	2.8	7.3
11	Left Gantry	9.3	9.8	9.6	10.3	2.8	2.1	7.0	14.2	1.79	1.53	1.25	2.13
12	Left Gantry	0.9	1.33	1.36	1.34	10	8.9	1.19	1.27	3.4	4.1	13.7	6.7
13	Table – Orbit Left	1.54	1.21	1.66	1.87	8.6	6.7	1.07	1.34	3.1	5.4	10.6	6.8
14	Table Left	1.23	1.55	1.8	2.06	1.92	1.81	0.88	1.38	2.82	4.5	2.81	1.67
15	Control Console	0.55		0.92		0.3		1.97		1.89		0.28	

workload per treatment is designed to be 6,250 monitor units (MU) using a 25 mm tungsten collimator. Therefore, the estimated annual workload for treatments is 1.4×10^7 MU. Accounting for the quality assurance measurements, that can add the workload of 3.38 million MU. The total annual workload is 1.7×10^7 MU. The "Beam-On" time of the ZAP-X is 194 h y^{-1} at the dose rate of 1,500 MU min^{-1}. Furthermore, the duty cycle (D/C) of 9.7% is obtained by dividing 194 "Beam-On" hours over the standard 2,000 work hours per year, resulting in 9.7% of the time the beam was energized for treatments (NCRP 2005). The public is allowed to receive 1 mSv y^{-1} or 0.5 μSv in any 1 hour. Applying the duty cycle factor of 0.097, the allowable instantaneous dose rate for the public is 5.15 μSv h^{-1}. The highest value in this measurement is 25.3 μSv h^{-1}. Taking into account the use factor of 0.2 (Weidlich et al. 2017), the measurement dose rate is adjusted to 5.06 μSv h^{-1}, which is below this limit of 5.15 μSv h^{-1}. The use factor of 0.2 was established by comparing the solid angle on a sphere spanned by individual treatment nodes compared to the solid angle spanned by all treatment nodes.

Radiation dose assessed according to Chinese standards. According to the standard GBZ 121-2020 (NHCPRC 2020), the allowable reference control dose rate outside the treatment room wall and the entrance was determined as follows:

1. According to the weekly dose reference control level, H_c, the dose rate reference control level of the focus point $H_{c,d}$ (μSv h^{-1}) was calculated based on the weekly workload (W), use factor (U), and the occupancy factor (T). The value of H_c for the staff in the control area outside the radiotherapy room and the personnel in non-controlled areas outside the radiotherapy room is $H_c \leq 100 \ \mu$Sv h^{-1} and $H_c \leq 5 \ \mu$Sv wk^{-1}, respectively.

2. According to the different occupancy factors of the focus points, the highest reference control level of the dose rate $\dot{H}_{c,max}$ (μSv h^{-1}) was determined. The $\dot{H}_{c,max}$ for T ≥ 1/2 and T<1/2 is $\dot{H}_{c,max} \leq 2.5 \ \mu$Sv h^{-1} and $\dot{H}_{c,max} \leq 10 \ \mu$Sv h^{-1}, respectively.
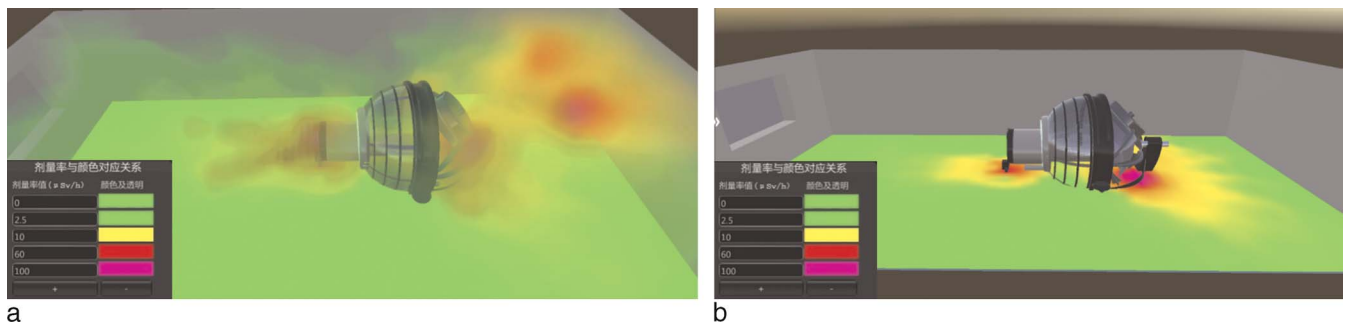

Fig. 6. Radiation field distribution of Zap-X system with gantry at home position: (a) 3D radiation field distribution, (b) 2D projection of the radiation field on a plane at the height of isocenter.

Table 3. Comparison between Chinese standards and American standards.

	Chinese (GBZ 121-2020)	US (NCRP 151)
Dose limit for public	Same (1 mSv y^{-1})	
Max. allowable dose rate	Instantaneous dose rate (10 μSv h^{-1})	Time averaged dose rate (20 μSv in any 1 h)
Occupancy factor	Same (<1/2)	
Use factor	0.25	0.20
Duty cycle	Not accounted for	0.097
Method of calculation	Same (workload based including scaling factors such as use factor and occupancy factor)	

3. Comparing the value of $\dot{H}_{c,d}$ with $\dot{H}_{c,\max}$, the smaller one was selected as the dose rate reference control level.

The calculation method of $\dot{H}_{c,d}$ is as follows:

$$\dot{H}_{c,d} = \frac{H_C}{t \cdot U \cdot T} \qquad (2)$$

where

$\dot{H}_{c,d}$ = the dose rate reference control level;

H_C = dose control level for a week;

t = the time of irradiation during radiotherapy in a week;

U (use factor) = the percentage of time of radiation irradiated in a specific direction; and

T = the occupancy factor.

A self-shielding radiosurgery system like the Zap-X system is a new generation radiotherapy system. To date, there are no standards regulating the radiation shielding requirements for self-shielded systems in China. The reference control level of dose rate $\dot{H}_{c,d}$ was evaluated according to the GBZ 121-2020 (NHCPRC 2020).

For this device, H_C should be 5 μSv wk^{-1}, and t would be 3.13 h wk^{-1}. U should be 0.25 as described in GBZ/T 152-2002 (MHPRC 2002). T should be 0.25 according to GBZ 121-2020 (NHCPRC 2020). As occupationally exposed personnel will spend most of the time during treatment in the control room with very little time spent in the treatment room, an occupancy factor of 0.25 was assigned. That means that $\dot{H}_{c,d}$ is equal to 25.56 μSv h^{-1}. $\dot{H}_{c,\max}$ remains at 10 μSv h^{-1} for T < 1/2. According to the regulation, the minimum value of both $\dot{H}_{c,\max}$ and $\dot{H}_{c,d}$ should be taken. Therefore, since 25.56 μSv h^{-1} > 10 μSv h^{-1}, the control value $\dot{H}_c$ should be 10.0 μSv h^{-1}. According to the results in survey cases, some of the measurement dose rates did not meet this limit.

Differences between international standards and Chinese standards. International standards are mainly concerned with the annual permissible dose equivalent for occupationally exposed personnel and the annual dose equivalent for the public. As mentioned above, according to the calculations of various parameters for Zap-X, the limit value of instantaneous dose rate is 32 μSv h^{-1}, which is obtained by dividing the 6.41 μSv h^{-1} calculated by the use factor of 0.2 mentioned above. This limit is higher than the maximum dose rate of 25.3 μSv h^{-1} that occurs during the measurement of Zap-X, which means that the Zap-X treatment room would not need to be controlled, and the public is considered properly protected in this area. By international standards, the radiation shielding required to protect the public is entirely provided by the material embedded in the housing of the Zap-X system when measured at 1 m from the device perimeter.

In order to ensure personnel safety and facilitate the unification of standards, the Chinese standard uses the instantaneous dose rate value derived from different conditions to provide the most conservative approach to shielding. As mentioned above, in the case of Zap-X, the calculated values of $\dot{H}_{c,d}$ and $\dot{H}_{c,\max}$ are, respectively, 25.56 μSv h^{-1} and 10 μSv h^{-1}. Therefore, 10.0 μSv h^{-1} should be the limit according to the regulations. Consequently, in the current situation, many survey stations are not properly protected by the self-shielding material of the Zap-X according to the Chinese standards. In order to reduce the instantaneous dose rate from 25.56 μSv h^{-1} to 10 μSv h^{-1}, additional steel shielding of 0.4 TVL or 3.5 cm thickness would have to be added.

The relevant standards of the radiation shielding of the treatment room are the main basis for the environmental impact assessment and occupational hazard assessment of related radiotherapy projects. By comparing Chinese and international standards, the current radiation shielding standards system for the radiotherapy room of an electron linear accelerator in China are basically the same as the relevant international standards. The main difference is the dose reference control level. In addition to the difference in the weekly dose control target value (P), NCRP Report 151, the current ionizing radiation regulations in the United Kingdom (NCRP 2017; UK Statutory Instruments 2017), and the current Chinese standard take advantage of the average dose equivalent rate in any one hour, using time averaged dose rate (TADR) and instantaneous dose rate as evaluation indicators, which led to stricter shielding design requirements for the radiotherapy room.

CONCLUSION

According to international standards, the results of radiation shielding evaluation showed that the built-in shielding provided with the ZAP-X system for a referenced maximum workload of 3 patients per day with 3 targets each, 2,000 cGy to 80% per treatment with a 25-mm collimator is sufficient to provide radiation levels that will not exceed the annual permissible dose equivalent for the public of 1.0 mSv. No occupational restrictions other than those imposed by the laser scanner proximity detector will have to be implemented in adjacent offices nor above the treatment room to ensure the safety of non-radiation workers occupying these areas.

According to Chinese practice, the most stringent dose limit is used when a facility is evaluated for compliance to the standards. As such, the requirement of H_c is used as the acceptable dose limit. The results of radiation measurement showed that the radiation protection effect of Zap-X cannot meet the radiation protection requirements of Chinese relevant standards without the shielded treatment room. In general, additional shielding to the wall of the treatment room or an increase in treatment room size could be employed to meet the requirements of radiation protection regulations.

As the Zap-X presents a new generation of self-shielded radiosurgery devices, the Chinese standards should take into account the technical development. When evaluating the measured instantaneous dose rates, the actual utilization of the machine should be considered. Besides the use factor and the occupancy factor, the factor of duty cycle could be introduced for the future Chinese regulations to provide a more relevant approach to shielding design. Not accounting for these operating conditions will result in a gross overestimation of the shielding requirements. In general, the current regulations would hinder the promotion and application of a new generation of radiotherapy equipment, such as the self-shielded Zap-X system.

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