STUDY ON OCCUPATIONAL EXPOSURE OF MEDICAL STAFF CAUSED BY INDUCED RADIOACTIVITY IN THE TREATMENT ROOM OF MEDICAL HEAVY-ION FACILITY

by

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Heavy-ion radiotherapy is currently recognized as the most advanced particle therapy method and is being vigorously promoted and applied worldwide. This method can rapidly generate radiation and induce radioactivity during treatment. However, the induced radioactivity, which is the primary source of exposure for medical staff, does not disappear following therapeutic application in the treatment room. In this study, we investigated the characteristics, dose rate distribution, and impact of this induced radioactivity on medical staff in the treatment room (uniform scanning mode) at Gansu Wuwei Tumor Hospital using experimental measurement and Monte Carlo simulation. We found that the exposure dose experienced by medical staff is predominantly related to the irradiated patients for single irradiation and the irradiated beam delivery system for long-term irradiation. The half-lives of the main radionuclides ranged from a few minutes to tens of minutes for single irradiation and from tens of days to hundreds of days for long-term irradiation. The primary radionuclide contributors are ^{15}O, ^{11}C, ^{176}Ta, and ^{177}W. We also estimated the personal dose experienced by the medical staff in the treatment room in relation to their working patterns. The results showed that the maximum annual exposure dose of medical staff in the horizontal treatment direction under the current model was 0.728 mSv. We hypothesized that an appropriate increase in the patient's treatment could reduce the annual exposure dose of medical staff to 0.650 mSv without changing the total treatment time per day. Finally, some suggestions were made to reduce the exposure of medical staff to unwanted radiation.

Key words: heavy ion, Monte Carlo, induced radioactivity, dose assessment

INTRODUCTION

Particle radiation therapy technology has been applied in clinical practice since 1954 when it was first used at Lawrence Berkeley National Laboratory [1]. The major advantage of this technology is that the proton and carbon ions used in this therapy provide an effective dose distribution while preserving normal tissues around the tumor [2]. Carbon ions are considered to be the most balanced particles with a Bragg peak and more significant relative biological effectiveness [3]. This means that they are more likely to be able to control tumors. An increasing number of medical facilities are being introduced to apply this technology clinical in different institutions worldwide [4]. The induced radioactivity can be generated through nuclear reactions when the primary beam and secondary particles react with materials such as components, air, and the patient's body [5, 6]. However, this induced radioactivity is the leading cause of exposure to medical staff and is associated with a wide distribution. The quantity of induced radiation depends on the composition of the materials, the size of the activation cross-section, the run time of the accelerator, and the decay time after the run stops [7].

The characteristics of induced radioactivity have been studied extensively. Agosteo [8] showed that the primary source of secondary neutrons in the treatment room was the patient's body which represented a non-negligible secondary radiation source. Research by Xu *et al*. [9] subsequently indicated that air and cooling water activation was unimportant concerning the environment and medical staff. Wu *et al*. [10] described the patient-induced radioactivity during treatment theoretically and analyzed the activity buildup process of periodic irradiation, deriving the buildup formulas. Tujii *et al*. [11] measured the activation levels of both therapeu-

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tic devices and the radiation provided to patients and used this information to assess the maximum dose received by medical staff. However, these previous findings focused on patients, environmental media, or components, and did not systematically analyze the induced radioactivity of the entire treatment room, using simulation or experimental measurements alone. In the present study, we used two methods to conduct a systematic study of induced radioactivity in the treatment room and to evaluate the exposure dose incurred by medical staff.

For example, Gansu Heavy Ion Tumor Hospital features a therapeutic center that is composed of a carbon ion facility that was independently developed by the Institute of Modern Physics, Chinese Academy of Science. This center has been used for clinical trials since 2018 and was officially put into clinical use in March 2020. The center features a cyclotron that is used as an injector, a synchrotron, beam transport lines, and four treatment rooms, with uniform scanning (US) and pencil beam scanning modes. The center can offer carbon beams from 120-400 MeV/u ("u" represents nucleon) with a maximum beam current intensity of up to 1 10^8 particles per second (pps) [12].

In the present study, we used experimental measurements and Monte Carlo simulation to investigate the radioactivity induced in treatment Room 2 of this center which has two beam delivery systems (BDS), horizontal and vertical. The beam is deposited in a patient's tumor after passing through the BDS and compensator during treatment. Based on the primary working areas and work patterns of the medical staff involved, the exposure of medical staff to radioactivity is primarily the result of the induced radioactivity generated by the multi-leaf collimator (MLC), compensator, treatment bed, beam dump, and the patient's body. The workflow for medical staff is shown in fig. 1.

Clinical data indicated that the most commonly used energy was 330 MeV/u, the beam current intensity ranged from 2.7 10^7 to 4.2 10^7 pps and the irradiation time ranged from 2 to 11 minutes. Thus, the therapeutic energy was set to 330 MeV/u and the beam current intensity was set to 3.7 10^7 pps for single irradiation in FLUKA code. It was assumed that the mean irradiation schedule was 5 minutes with 30 treatment times per day, 5 working days per week, and 50 working weeks per year according to hospital conditions.

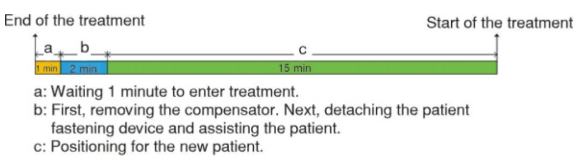

Figure 1. Diagram showing the workflow performed by medical staff

MATERIALS AND METHODS

The treatment room operated under US mode and the BDS system was a fully passive system with fixed beam modulation. The components of the room mainly included the BDS, a compensator, a treatment bed, digital radiography (DR) equipment, and a beam dump. The BDS system featured a primary collimator, a ridge filter, an MLC, and a bracket. Figure 2 shows the layout of treatment Room 2.

Monte Carlo method

In this study, we used the FLUKA [13-15] code to calculate the induced radioactivity. This is a comprehensive Monte Carlo simulation tool for particle transport and material interactions. The application of this method includes the shielding design of the accelerators, material activation, radioactivity, and radiation therapy. This method provides accurate simulations of more than 60 different particles with energies ranging from keV to TeV and enables online temporal inference and tracking of the radiation generated by unstable radionuclides [16]. The FLUKA version 2021.0 Istituto Nazionale di Fisica Nucleare (INFN) was used to calculate the radionuclides and their activity and dose rate distributions produced in the treatment room.

The physical process of heavy ions interacting with matter is explained by the PHYSICAL card and involves the collision process, the evaporation process of particles in the evaporation model, and the activation of coalescence mechanisms. For nuclear reactions induced by neutron activation, low-energy neutron transport (LOW-NEUT) must be activated. Irradiation of the treatment room and cooling times are described by the IRRPROFI card and DCYTIMES card, both of which were measured in seconds. The combination of the USRBIN card and the AUXSCOR card can determine the dose equivalent rate distribution around the treatment room. The conversion factor AMB74, from International Commission on Radiological Protection (ICRP), Report No. 74, [17] in the AUXSCOR card was used to convert the fluence to ambient dose equivalent while the RESNUCLE card acts as a detector to identify radionuclides in the detection area. Before running the simulation, it was necessary to link the heavy ion database Idpmqdm which script to link FLUKA with RQMD – 2.4 [18] and DPMJET – 3 [19] to achieve the heavy ion nuclear reaction process.

Figure 2 shows that the MLC and bracket were the main considerations in the BDS for FLUKA modeling due to their respective roles in the shielding wall. Since the structure of the MLC and compensator are complex, both of the FLUKA models were simplified for the convenience of calculation. Figure 3 shows the FLUKA calculation model in the horizontal treatment direction. The relevant physical and geometric parameters are shown in tab. 1. The beam shape was rectan-

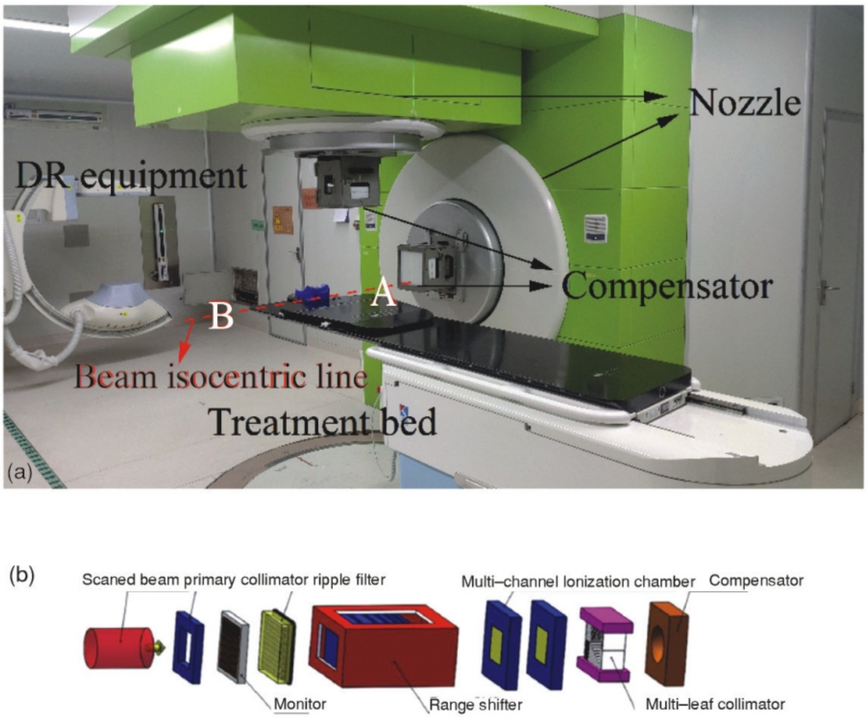

Figure 2. The layout of treatment Room 2; (a) the composition of the treatment room and (b) the composition of the nozzle

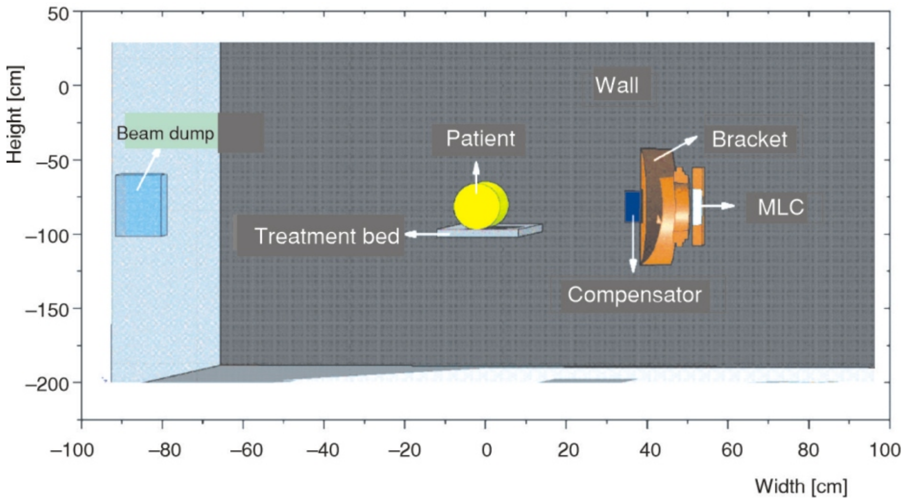

Figure 3. The FLUKA model of the treatment room in the horizontal treatment direction

gular (15 cm 15 cm) on the *X*- and *Y*-axes. An 8 cm 8 cm 6 cm rectangle filled with air acted as a grid in the middle of the MLC, and a 8 cm 7.5 cm cylinder was filled with air to represent the shape of the patient's tumor in the middle of the compensator. The size of the treatment room was 16.98 m 10.90 m 4 m and was filled with air. The centers of the MLC, compensator, patient, and beam dump were on the isocentric beam line.

Experimental method

Experimental measurements were recorded for one week starting on the January 4, 2021. Dose equivalent rates were measured using a Fluke 451P ionization chamber positioned 5 cm above the surface of the patient's body and at Positions A and B (as shown in fig. 2) at a point 10 cm from the bed, representing the typical working positions of medical staff. The detector could detect γ and X-rays >25 keV in the measurement range of 0-5 $mSvh^{-1}$ and had a linear error of 10 %, a response time of 1.8 seconds, and was calibrated before experimental measurements.

While the patient was undergoing treatment, the researcher recorded treatment energy, total particle numbers, and irradiation time. After treatment, the researcher entered the treatment room and placed the detector 5 cm above the patient's treatment area for 6 seconds before recording the stabilized value and the values at Positions A and B using the same method.

Table 1. The compositions and dimensions of components in the treatment room

Component	Material	Element	Proportion	Density [gcm^{-3}]	Dimensions
MLC	Tungsten	W	1.0	19.3	35.5 cm 6 cm
Compensator	Teflon	C	0.3871	2.2	20 cm 20 cm 10 cm
		F	0.6129		
Patient	Tissue	H	0.101172	1.0	30 cm 81 cm
		C	0.111		
		N			
		O	0.761828		
Beam dump	Water	H	0.111111	1.0	30 cm 40 cm 30 cm
		O	0.8889		
Treatment bed	Carbon fiber	C	1.0	1.0	243 cm 53 cm 5 cm
Wall	Concrete	H	0.01	2.3	–
		C	0.001		
		O	0.529107		
		Na	0.016		
		Mg	0.002		
		Al	0.033872		
		Si	0.337021		
		K	0.013		
		Ca	0.044		
		Fe	0.014		
Air	Air	C	0.0001248	0.0012	–
		N	0.755267		
		O	0.231781		
		Ar	0.012827		
Bracket	Iron	Fe	1.0	7.874	–

SOURCE TERM ANALYSIS

The radioactivity induced in the treatment room was investigated by FLUKA modeling. The irradiation time was 5 minutes and 15 years for single irradiation and long-term irradiation, respectively. The single irradiation and long-term irradiation correspond to a single treatment for the patient and the service time of the facility, 15 years was considered as approximately half the lifetime of the facility. For long-term irradiation, the average beam current intensity (the total number of particles of irradiation divided by the running time) was adopted. The interval between facility rest was far less than the running time of the facility and the half-lives of long-lived radionuclides, as shown in eq. (1).

$$\frac{1\ 10^{8}\ \text{pps}\ (5\,\text{min}\ \ 30\ \text{person}\ \ 5\ \text{days}\ \ 50\ \text{weeks}\ \ 60\ \text{s})}{365\ \text{days}\ \ 24\ \text{h}\ \ 3600\ \text{s}}\ \ 7.1\ 10^{6}\ \text{pps} \qquad (1)$$

The radionuclide calculation results showed that most of the radionuclides related to β^{+} decay, followed by β^{-} decay, reduced electron capture, and α decay. Due to the relatively short range of β^{+} and β^{-} in air, the γ rays produced by radionuclides and positron annihilation represented the primary source of external radiation dose for medical staff. The dose contribution of the radionuclides was calculated by combining their activity and the gamma-ray constant [20-22]. Table 2 describes the main radionuclides and their gamma dose contribution rates when components are cooled for 1 minute. Radionuclide dose contributions of less than 2 % and 1 % produced in the MLC and other components are not listed in tab. 2. All components in the treatment room would be expected to be irradiated over a long period except for the patient, the air, and the compensator. The major dose contributors in the patient's body, air, compensator, and beam dump are ^{11}C, ^{13}N, ^{15}O, ^{41}Ar in the air, and ^{18}F in the compensator. Long-lived radionuclides, such as ^{3}H, ^{7}Be, ^{22}Na, ^{182}Ta, and others, are known to accumulate during long-term irradiation. The half-lives of these radionuclides range from several decades to many years. The major radionuclides produced in the wall are ^{28}Al and ^{24}Na while those produced in the bracket are ^{53}Fe, ^{52m}Mn, and ^{56}Mn. More than 1300 induced radionuclides are produced in the MLC, of these the main radionuclides undergoing accumulation due to long-term irradiation that form the predominant exposure to medical staff are ^{178m}Ta, ^{176}Ta, ^{187}W, and ^{175}Ta. These radionuclides have half-lives ranging from hours to dozens of hours.

Our analysis of the surface dose rate for the MLC after long-term irradiation showed that the induced radioactivity of the MLC after 10 years of irradiation was close to the saturation state, and that of MLC after

Table 2. The main radionuclides and their gamma dose contributions in components after 1 minute of cooling

Component	Nuclide	Half-life	Single irradiation		Long-term irradiation	
			Activity [Bq]	Dose contribution [%]	Activity [Bq]	Dose contribution [%]
Patient (tissue)	C-11	20.33 min	2.78 10^5	35.07	*	*
	N-13	9.965 min	3.44 10^4	3.97	*	*
	O-15	122.24 s	4.79 10^5	60.96	*	*
Treatment bed	C-11	20.33 min	7.74 10^4	100.00	2.10 10^4	100.00
	H-3	12.33 year	*	*	*	*
Beam dump	C-11	20.33 min	1.18 10^4	15.49	1.98 10^5	47.73
	N-13	9.965 min	3.69 10^3	4.41	2.288 10^4	5.00
	O-15	122.24 s	6.08 10^4	80.11	1.90 10^5	46.02
	H-3	12.33 year	*	*	2.00 10^5	*
	Be-7	53.12 d	*	*	1.16 10^5	1.25
Air	C-11	20.33 min	6.34 10^3	24.48	*	*
	N-13	9.965 min	1.06 10^4	37.18	*	*
	O-15	122.24 s	8.91 10^3	34.57	*	*
	Ar-41	109.61 min	9.90 10^2	3.77	*	*
Compensator	C-11	20.33 min	1.19 10^5	57.24	*	*
	N-13	9.965 min	1.46 10^4	6.40	*	*
	O-15	122.24 s	3.33 10^4	16.07	*	*
	F-18	109.77 min	3.61 10^4	20.29	*	*
Wall	C-11	20.33 min	5.28 10^5	2.52	3.70 10^5	2.60
	O-15	122.24 s	2.59 10^6	12.45	5.39 10^5	3.81
	Al-28	2.24 min	1.34 10^7	80.09	2.68 10^6	23.49
	Na-24	14.96 h	1.39 10^5	1.80	3.45 10^6	65.67
	H-3	12.33 year	*	*	5.09 10^5	*
	Na-22	2.60 year	*	*	1.85 10^5	2.34
	Others		*	3.14	*	2.09
MLC	C-11	20.33 min	1.12 10^5	5.87	*	*
	Dy-149	4.20 min	3.82 10^4	2.94	*	*
	Lu-165	10.74 min	6.51 10^4	3.49	*	*
	Hf-167	2.05 min	1.12 10^5	3.53	*	*
	Hf-169	3.24 min	1.73 10^5	5.72	*	*
	Ta-170	6.76 min	1.23 10^5	6.61	*	*
	Ta-172	36.8 min	6.09 10^4	4.92	*	*
	Ta-178m	2.36 h	8.90 10^4	5.12	6.37 10^5	13.93
	W-177	132 min	8.37 10^4	3.74	3.43 10^5	5.82
	W-179	37.05 min	5.44 10^5	2.14	*	*
	Re-179	19.5 min	7.76 10^4	4.01	*	*
	Re-180	2.44 min	1.91 10^5	11.21	*	*
	W-187	23.72 h	*	*	4.99 10^5	4.79
	Lu-170	2.012 d	*	*	8.95 10^4	3.20
	Lu-172	6.70 d	*	*	1.42 10^5	4.54
	Ta-172	36.8 min	*	*	9.57 10^4	2.93
	Ta-174	1.05 h	*	*	1.92 10^5	3.35
	Ta-175	10.5 h	*	*	2.53 10^5	4.96
	Ta-176	8.09 h	*	*	3.68 10^5	13.74
	Ta-182	114.43 d	*	*	1.18 10^5	2.47
	Others		*	40.7	*	40.27
Bracket	Fe-53	8.51 min	2.96 10^4	37.17	9.77 10^3	5.67
	Mn-51	46.2 min	2.38 10^3	2.56	3.14 10^3	1.56
	Mn-52m	21.1 min	1.77 10^4	42.37	1.28 10^4	14.16
	Mn-56	2.58 h	1.10 10^4	15.50	4.59 10^4	32.48
	Cr-49	42.3 min	2.31 10^3	2.41	3.20 10^3	1.54
	Mn-54	312.3 d	*	*	1.24 10^5	44.03
	Others		*	*	*	0.57

* The gamma dose contribution of radionuclides less than 2 % is not listed for single irradiation and less than 1 % is not listed for long-term irradiation

1 year of irradiation reached 95 % of the saturation state. This means that subjects/staff will be exposed to the MLC as soon as they enter the treatment room; this has been published previously [23]. Consequently, the long-lived radionuclides produced in the MLC should not be ignored.

The induced radioactivity produced in the air can cause both internal and external radiation exposure to the human body. Generally, ventilation is used to reduce the concentration of radionuclides in the treatment room to reduce the levels of radiation in the treatment room. The dose levels incurred by the human body due to air-induced radioactivity in a treatment room have been investigated previously [23], these studies have shown the effect of air-induced radioactivity was negligible.

THE DISTRIBUTION OF DOSE RATE WITH REGARD TO WORK REFERENCE POINTS

Based on previous research, this study used experimental measurements and Monte Carlo analysis to investigate the ambient dose equivalent distribution of the working area occupied by medical staff in the treatment room.

Experimental results and comparisons with calculated data

A total of 49 experiments were conducted on 17 patients in this study. One patient was chosen for each treatment energy. For each patient, the beam and other relevant parameters were input into the FLUKA code for simulation. The shape of the compensator for each patient in the FLUKA model was adjusted as necessary to approximate the real scenario. The dose rates on the body surface of the patient obtained by experimental measurement and FLUKA calculations are

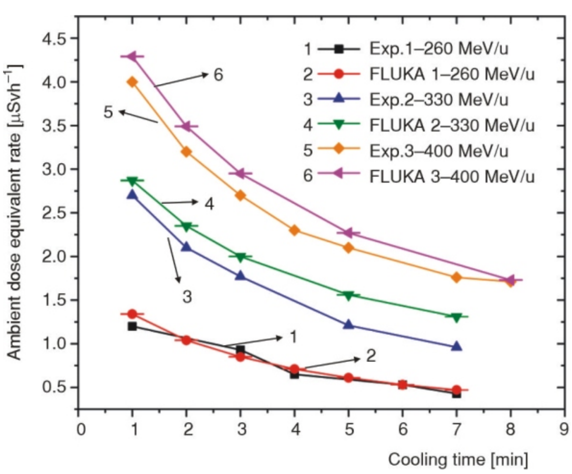

Figure 4. The dose rates of FLUKA simulation and experimental measurement

given in fig. 4. The background value measured in the treatment room was 0.06-0.15 Svh^{-1}, this is given as 0.1 Svh^{-1}in fig. 4. The experimental results were concordant with the FLUKA calculation results. The differences between the two may be caused by the simplification of the model, the position of the detector, and the linear error of the detector. The linear error of the 451P was 0.1 and the error related to the FLUKA calculation was 0.005.

The FLUKA can be used to calculate the residual dose rate at any time and position, furthermore, results can be confirmed to be credible by experimental observation. This represents a significant advantage over experimental measurement. Therefore, FLUKA was used to investigate the dose contribution of each component in the treatment room.

Effects of each component on medical staff

To investigate the contribution of each component to the measuring point more comprehensively, we used the fractional step method to analyze the contribution of each component to Positions A and B with FLUKA code. It was necessary to remove each component from the treatment room to calculate the dose rate of each component to the measurement points. Figure 5 shows the variation of dose rate contributions of different components at Positions A and B over time after removing the compensator.

Figure 5 shows that each component made different contributions to the dose rates at Positions A and

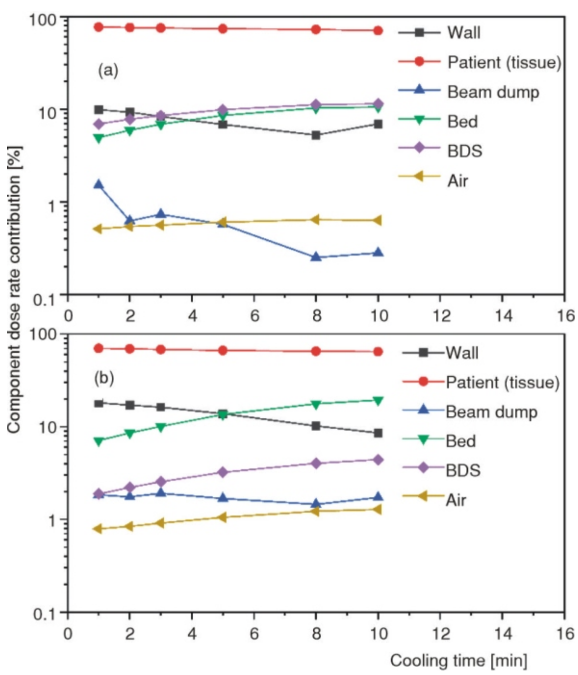

Figure 5. The dose rate contribution of components with time at Positions A and B for single irradiation; (a) Position A for staff and (b) Position B for staff

B, the patient was the major contributor at both two points. The dose contribution of the wall at the two points reduced over time because the main radionuclides produced in the wall after single irradiation were dominated by ^{28}Al and ^{15}O for 10 minutes of cooling, with half-lives of 2.24 minutes and 2.04 minutes, respectively. Both radionuclides were much smaller than the half-lives of the main radionuclides produced in the treatment bed and the BDS. At Position A, the contribution rate of the beam dump and the air was generally <2 %. The dose contribution of the BDS was larger than that of the treatment bed because the half-lives of the major radionuclides produced in the BDS were larger than that of the treatment bed. Position B was relatively far from the BDS and the half-lives of the radionuclides produced in the BDS were larger than in the other components, thus, the dose contribution of the BDS to Position B increased over time.

The compensator is specially configured according to the tumor shape of each patient and the residual dose with cooling time at different distances from the compensator isocentric line are shown in fig. 6. Analysis showed that the dose changed rapidly at a distance of 0-10 cm but changed slowly at a distance of 10-20 cm. This is because the radionuclides produced in the compensator (mainly decay β^+) and the resulting positrons were blocked in the air, thus losing their kinetic

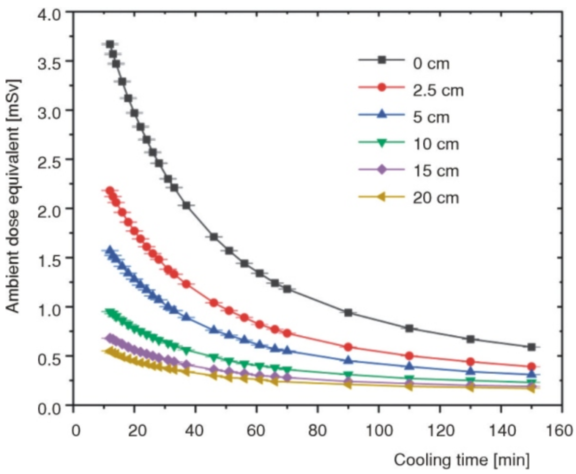

Figure 6. The residual dose at different distances from the compensator with time (400 MeV/u, 2.4 10^7 pps, irradiation time of 18 minutes)

energy and eventually combining with electrons to emit two 511 keV photons in opposite directions. The main radionuclide produced in the compensator (^{18}F) has a half-life of 109.77 minutes, thus, the dose is still present on the surface of the compensator after cooling for 2 hours. It is recommended that medical staff maintain a distance of more than 10 cm from the compensator during operation and stay away from the compensator during times of non-operation.

DOSE ASSESSMENT

Based on previous studies, the Monte Carlo method can be used in combination with the working mode of medical staff to evaluate exposure doses in typical positions. In the calculation, the therapeutic energy was set to 330 MeV/u, the irradiation time was set to 5 minutes for single irradiation with a beam intensity of 3.7 10^7 pps, and the irradiation time was set to 1 year for long-term irradiation with a beam intensity of 7.1 10^6 pps.

Combined with the data shown in tab. 2, we found that medical staff was mainly exposed to ^{15}O and ^{11}C generated in the patients and long-lived radionuclides generated in the MLC. Increasing the waiting time for cooling and reducing the number of visits to the treatment room are effective methods for medical staff to reduce the exposure dose. For the same patient, a single high dose can be used to reduce the number of times the patient enters the treatment room within the prescribed dose. The physiotherapist can then make different therapeutic plans according to the condition of the patients. The exposure doses for medical staff are shown in tab. 3 concerning the mean irradiation time for 10 minutes with 20 instances of irradiation per day as an example, other conditions remained unchanged in the treatment room. Thus the average beam current intensity was changed by applying eq. (2)

$$\frac{1\;10^8\,\text{pps}\;(10\,\text{min}\;\;20\,\text{person}\;\;5\,\text{days}\;\;50\,\text{weeks}\;\;60\,\text{s})}{365\,\text{days}\;\;24\,\text{h}\;\;3600\,\text{s}}\;\;9.5\;10^6\,\text{pps} \tag{2}$$

The results in tab. 3 show that increasing the patient's single prescribed dose can reduce the number of times medical staff enters the treatment room per day

Table 3. Exposure doses received by medical staff were evaluated at different treatment frequencies by FLUKA

Work task (see fig. 1)	A ($FLUKA_1$)	B ($FLUKA_1$)	A ($FLUKA_2$)	B ($FLUKA_2$)
	5 minutes per treatment and 30 times per day		10 minutes per treatment and 20 times per day	
b [Sv]	0.048	0.034	0.064	0.045
c [Sv]	0.049	0.037	0.066	0.049
Total dose for single [Sv]	0.097	0.071	0.130	0.094
Total number of the patient per year	7500		5000	
Annual exposure [mSv]	0.728	0.533	0.650	0.470

and thus reduce the annual exposure incurred by staff. The medical staff wear direct reading personal dosimeters at work, their cumulative doses in a single workflow were below the dosimeter's minimum. Therefore, thermoluminescence personal dosimeters were used to obtain the annual dose incurred by medical staff in 2021. The annual dose of most staff in the hospital was approximately 0.2 mSv and the maximum value was 0.96 mSv. These values were less than the occupational exposure dose limit of 20 mSv recommended by ICRP Report No. 103 [24].

CONCLUSIONS

The induced radioactivity produced in the treatment room was investigated in US mode which requires the support of multiple components to reach the patient's tumor for treatment. Thus, part of the beam is lost from the components along the way. Key radionuclides, such as ^{24}Na, ^{175}Ta, ^{176}Ta, ^{172}Lu, ^{178}W, and others, can irradiate medical staff every time they enter the treatment room and even when they are not providing treatment. Therefore, it is crucial to investigate the accumulation of radionuclides in components under long-term irradiation.

We found that most of the radionuclides produced in the treatment room were electron emissions and gamma rays were the main source of external exposure for medical staff. The patients themselves and the MLC were found to be the primary contributors to the exposure dose incurred by medical staff for single and long-term irradiation, respectively. The radionuclides produced in irradiated patients are mainly ^{15}O and ^{11}C. Increasing the cooling time is an effective means to reduce the exposure of medical staff to both radionuclides. We also found that the working positions of medical staff also affected the exposure doses they received while analysis of the exposure doses at Positions A and B showed that the exposure dose at A was 1.4-fold higher than that at B.

Although the dose assessment results in the current study were far less than the limit recommended by the ICRP, our data suggest that medical staff at Positions A and B should be rotated to reduce the exposure dose of staff at A and to appropriately increase the single therapeutic dose of patients to reduce the number of times medical staff enters the treatment room. Finally, medical staff should maintain a distance of more than 10 cm when touching the compensator.

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AUTHORS CONTRIBUTIONS

Changli Luo: writing-original draft, software, investigation, methodology, data curation. Wuyuan Li: supervision, conceptualization. Bo Yang: software, data curation. Youwu Su: supervision, conceptualization, methodology. Yang Li: software. Shakhboz Khasanova: writing. Wang Mao: methodology. Xuebo Liu: data curation. Weiwei Yan: supervision. Zongqiang Li: methodology.

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СТУДИЈА О ПРОФЕСИОНАЛНОМ ИЗЛАГАЊУ МЕДИЦИНСКОГ ОСОБЉА ИЗАЗВАНОМ ИНДУКОВАНОМ РАДИОАКТИВНОШЋУ У САЛИ ЗА ТРЕТМАН МЕДИЦИНСКОГ ТЕШКО-ЈОНСКОГ ПОСТРОЈЕЊА

Тренутно је радиотерапија тешким јонима призната као најнапреднија метода терапије честицама и снажно се промовише и примењује широм света. Ова метода може брзо да генерише зрачење и индукује радиоактивност током лечења. Међутим, индукована радиоактивност, која је примарни извор изложености медицинског особља, не нестаје након терапијске примене у сали за лечење. У овој студији, користећи експериментално мерење и Монте Карло симулацију, истражили смо карактеристике, дистрибуцију јачине дозе и утицај ове индуковане радиоактивности на медицинско особље у сали за лечење (униформни режим скенирања) у болници за туморе Гансу Вувеј. Открили смо да се доза излагања коју доживљава медицинско особље претежно односи на озрачене пацијенте за једно зрачење и систем за испоруку зрака за дуготрајно зрачење. Време полураспада главних радионуклида кретало се од неколико минута до десетина минута за једно зрачење и од десетина дана до стотина дана за дуготрајно зрачење. Примарни допринос је од радионуклида ^{15}O, ^{11}C, ^{176}Ta и ^{177}W. Такође смо проценили индивидуалну дозу коју прима медицинско особље у сали за лечење у односу на радне обавезе. Резултати су показали да је максимална годишња доза излагања медицинског особља у хоризонталној равни третмана према актуелном моделу износила 0,728 mSv. Претпоставили смо да би одговарајуће повећање третмана пацијената могло смањити годишњу дозу излагања медицинског особља на 0,650 mSv, без промене укупног времена лечења дневно. Коначно, изнети су неки предлози да се смањи изложеност медицинског особља нежељеном зрачењу.

Кључне речи: тешки јон, Монте Карло, индукована радиоактивност, процена дозе