Assessment of the induced radioactivity in the treatment room of the heavy-ion medical machine in Wuwei using PHITS (Postprint)

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Abstract

Carbon-ion radiotherapy (CIRT) offers unique physical and biological advantages over photon radiotherapy. However, some materials and devices in the CIRT treatment room become radioactive under bombardment by therapeutic carbon-ion beams due to nuclear reactions, thereby leading to possible radiation hazards to medical staff and additional and unwanted doses to patients. This study assessed the level of induced radioactivity in the treatment room of the Heavy-Ion Medical Machine (HIMM) in Wuwei. Monte Carlo simulations using PHITS were performed for a conservative case under the conditions of maximum beam energy and intensity provided by the HIMM facility. The geometry and configuration of Treatment Room 2 of the HIMM facility in Wuwei were adopted. We evaluated the activation of air, the phantom, and the components of the beamline, such as the primary collimator (PC), ridge filter (RF), and multileaf collimator (MLC). For air activation, we calculated the medical staff immersion external exposure and inhalation internal exposure caused by the corresponding radionuclides. For phantom activation, we estimated the additional dose to the patient's family members owing to secondary photons after treatment. In addition, the exemption or non-exemption of the component material activation was assessed. The results showed that external radiation caused by air activation was the main source of the annual effective dose at approximately 0.5 mSv/y. The induced radioactivity exposure to family members of a patient after CIRT was approximately 40 Sv, sufficiently lower than the public dose limit of 1 mSv/a. The induced radioactivity of the PC, RF, and MLC was all above the exempt levels after the devices were retired, whereas the induced radioactivity of the RS and compensator could reach the exempt levels after one patient session. Our study indicated that medical staff engaged in CIRT should stay away from the high-dose-rate area of induced radioactivity along the beam direction, shorten the residence time in the treatment room as much

as possible, and store the activated components in isolation after the equipment is out of use. Thus, this study provides guidance for accurately assessing the level of induced radioactivity in the treatment room for CIRT.

Full Text

Preamble

Assessment of Induced Radioactivity in the Treatment Room of the Heavy Ion Medical Machine in Wuwei Using PHITS

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Abstract: Carbon-ion radiotherapy (CIRT) offers unique physical and biological advantages over photon radiotherapy. However, some materials and devices in the CIRT treatment room become radioactive under bombardment by therapeutic carbon-ion beams due to nuclear reactions, leading to possible radiation hazards to medical staff and additional unwanted doses to patients. This study assessed the level of induced radioactivity in the treatment room of the Heavy-Ion Medical Machine (HIMM) in Wuwei. Monte Carlo simulations using PHITS were performed for a conservative case under the conditions of maximum beam energy and intensity provided by the HIMM facility, adopting the geometry and configuration of Treatment Room 2 at the Wuwei facility. We evaluated the activation of air, a phantom, and beamline components such as the primary collimator (PC), ridge filter (RF), and multileaf collimator (MLC). For air activation, we calculated both external exposure from immersion and internal exposure from inhalation for medical staff. For phantom activation, we estimated the additional dose to patients' family members from secondary photons after treatment. Additionally, we assessed whether component material activation met exemption criteria.

The results showed that external radiation from air activation was the main source of annual effective dose at approximately 0.5 mSv/y. The induced radioactivity exposure to family members of a patient after CIRT was approximately 40 Sv, sufficiently lower than the public dose limit of 1 mSv/a. The induced radioactivity of the PC, RF, and MLC all exceeded exempt levels after

device retirement, whereas the induced radioactivity of the RS and compensator could reach exempt levels after a single patient session. Our study indicates that medical staff engaged in CIRT should avoid high-dose-rate areas of induced radioactivity along the beam direction, minimize residence time in the treatment room, and store activated components in isolation after equipment decommissioning. Thus, this study provides guidance for accurately assessing induced radioactivity levels in CIRT treatment rooms.

Keywords: Induced radioactivity · Monte Carlo · CIRT · PHITS

1 Introduction

Compared to photons, heavy charged particles such as carbon ions simultaneously provide inverted depth-dose distributions and high relative biological effectiveness (RBE) for cancer radiotherapy [1]. These properties make heavy ions more destructive to target volumes while less injurious to surrounding healthy tissues.

Statistics from the Particle Therapy Co-Operative Group (PTCOG) show that by the end of 2020, more than 290,000 patients had been treated worldwide with particle therapy, including 40,000 treated with carbon ions (13.8% of the total), indicating that carbon-ion radiotherapy (CIRT) plays an increasingly important role in particle therapy. China has also been vigorously developing CIRT, with carbon-ion therapy systems under construction in Fujian and Zhejiang [2]. Consequently, radiation protection issues in CIRT have received greater attention because high-energy therapeutic carbon-ion beams necessary for deep-seated tumor treatment increase radioactivity. Induced radioactivity caused by therapeutic beams bombarding materials in the treatment room during CIRT gives medical staff and patients unwanted radiation doses [3]. Since induced radioactivity is often the main source of radiation dose for radiotherapy-related staff, it plays a significant role in treatment room radiation protection.

The physical basis of induced radioactivity is nuclear reaction, which only occurs when specific conditions are met. For incident neutrons, nuclear reactions occur regardless of energy because neutrons are unstable outside the nucleus and are always captured by other nuclei to stimulate nuclear reactions. However, for other particles, their energy must either reach the reaction threshold for neutron generation or be sufficiently large to cause nuclear fragmentation [4]. The energy range for CIRT is generally 80–430 MeV/u. Under such high beam energies, the conditions for nuclear reactions are fully satisfied. High-energy therapeutic carbon-ion beams produce secondary particles through inelastic nuclear interactions in beam delivery system devices, patients, etc. [5,6]. Most, but not all, of the radionuclides produced are short-lived. Neutron-deficient isotopes likely decay by positron emission or electron capture (EC), while isotopes with neutron excess likely decay by $\beta-$ emission. Because many of these decays result in excited isotopes, gamma rays are subsequently emitted, causing exposure to those present in the treatment room [7]. The Shanghai Proton and

Heavy Ion Center (SPHIC) assessed occupational exposure of medical staff in clinical practice due to radioactivity induced in patients' tumors to be approximately 0.508 mSv [8]. Although the dose level caused by induced radioactivity is low, this unwanted radiation should be minimized due to stochastic effects. Therefore, comprehensive study of the generation mechanism and spatial and temporal distribution characteristics of induced radioactivity in the treatment room is important for correctly understanding radiation hazards, formulating appropriate protection measures, and ensuring safety during radiotherapy and quality assurance.

This study conducted a systematic investigation of induced radioactivity in the CIRT treatment room using the Monte Carlo (MC) method after reviewing relevant literature [9]. The Institute of Modern Physics (IMP), Chinese Academy of Sciences, developed China's first medical carbon-ion therapy system, called the Heavy Ion Medical Machine (HIMM), in Wuwei. Currently, the HIMM facility has entered clinical application at Wuwei Heavy Ion Hospital. In this study, the geometry and configuration for MC simulation were established based on parameters of the horizontal beamline with a passive beam delivery system in Treatment Room 2 of the HIMM facility in Wuwei. Specific beam model establishment, parameter settings, and calculation formulas are explained in detail in the second section. The third section presents simulation and calculation results, from which important conclusions were drawn. This study evaluated induced radioactivity and secondary exposure to medical staff, the public, and patients' families in treatment rooms and provided radiation protection recommendations. Additionally, the degree of activation of different materials under heavy-ion irradiation was assessed to provide reference for disposal of out-of-service devices. The aim was to provide guidance for assessing induced radioactivity levels in CIRT radiotherapy treatment rooms.

2.1 Overview of PHITS

PHITS is an MC program package for studying particle and heavy ion transport. The heavy ion energies studied range from 10 to 100 GeV/u, and particle types include all ions (nuclei, nucleons, photons, electrons, muons, etc.) [10,11]. Because PHITS can transport ions, this MC program package is commonly used in heavy-ion therapy, space radiation, and radiation protection of heavy-ion accelerators. For CIRT simulation, PHITS has successfully reproduced dose distributions, including out-of-field doses, and secondary neutron production has been verified against experiments [12-15].

Activation calculation in PHITS must be combined with the DCHAIN-PHITS program (referred to as DCHAIN for brevity). DCHAIN is a decay chain analysis code for simulating production, buildup, burnup, and decay of nuclides as a function of time in any radiation environment. PHITS provides DCHAIN with neutron flux spectra and nuclides generated by high-energy nuclear reactions. DCHAIN performs decay chain analysis, ultimately outputting time-dependent nuclide inventories, decay heat, photon spectra, and effective dose rates [16].

Toyohara et al. calculated radioactivity using PHITS and DCHAIN to analyze experimental results, showing that the ratio of simulated to measured radioactivity was within 0.9–1.5 [17]. Therefore, using PHITS and DCHAIN to calculate induced radioactivity in this study is reasonable.

The [T-Dchain] tally is defined in PHITS to generate DCHAIN input files. In this simulation, we set intermittent irradiation mode according to actual conditions (8 s per pulse: 2 s beam-on, 6 s beam-off), with total irradiation time of 20 min. DCHAIN calculation relies on two primary types of nuclear data: neutron reaction cross-sections and decay data. We chose hybrid data libraries: the neutron reaction cross-section library was JENDL/AD-2017+JEFF-3.3+FENDL/A-3.0+JENDL-4.0+ENDF/B-VIII.0, and the decay data library was JENDL/DDF-2015+ENDF/B-VIII.0+ENSDF. This study adopted PHITS version 3.28 [18].

2.2 MC Simulation

The HIMM facility at Wuwei Heavy Ion Hospital has four treatment rooms. The first contains a horizontal beamline with spot scanning system, the second provides both horizontal and vertical passive beam delivery systems, the third provides a vertical beamline, and the fourth contains a 45° oblique beamline, all equipped with passive beam delivery systems [19] (Fig. 1 Figure 1: see original paper). This study established a simplified horizontal beamline from the second treatment room as the model basis. The treatment room model dimensions were 1130 cm × 1698 cm × 600 cm, with standard concrete walls of density 2.3 g/cm^3. The model was determined with reference to computer-aided design (CAD) drawings [20]. The beamline simulation included a pre-collimator (PC), ridge filter (RF), and multileaf collimator (MLC). The phantom was a 20 cm × 20 cm × 30 cm water tank irradiated by a 15 cm × 15 cm field with 2-cm SOBP (Spread-out Bragg Peak), located at the treatment room isocenter. Several idiosyncratic components (such as compensator and range shifter) were omitted from general calculations, though all were considered for material activation evaluation. In conclusion, we adapted two simplified beamlines to achieve different study aims (Fig. 1(b) and (c)). Transport of 1×10^8 carbon ions from the phase space file surface was simulated to achieve statistical uncertainties within 5% for most statistics, at the cost of increased CPU computing time [21]. (At some measurement points, fewer particles pass through, and even large numbers of simulations cannot reduce measurement error.) For conservative consideration, maximum beam current parameters of the HIMM facility were selected: beam energy of 400 MeV/u and current intensity of 4×10^8 pps. Main beam parameters are listed in Table 1 , where maximum depth corresponds to the carbon-ion beam range in water at maximum energy.

To achieve research objectives, measurement points were set every 50 cm from the isocenter in three directions for nine total points (distribution shown in Fig. 1(d)). The three directions were: beam direction, 45° right deviation from beam, and vertical right direction. Thus, only the radiation field on one side

was considered. Temporal curves of induced radioactivity dose rates at these nine points were output to describe spatial distribution and temporal changes. Additionally, a point 30 cm from the water phantom surface was of interest for evaluating dose to patients' family members from activated phantom.

2.3.1 Calculation of Dose to Medical Staff from Activated Air

Dose from activated air includes internal radiation dose (ingestion and inhalation) and external radiation dose (air immersion, surface deposition, and water immersion). Combined with actual treatment room conditions, we considered only inhalation internal irradiation and air immersion external irradiation. Activity-dose conversion factors for air immersion external exposure and inhalation dose conversion factors were obtained from ICRP reports [22,23] or GB18871-2002 [24].

Dose from air activation is often characterized by annual effective dose, the main source of professional radiation dose to medical staff. External immersion irradiation dose is considerably higher than internal radiation dose. Therefore, annual effective dose to medical staff from external air immersion exposure was the focus for assessing induced radioactivity levels. Radionuclides in treatment room air mainly derive from thermal neutron capture. First, concentration of each radionuclide induced by radiation in air was calculated using PHITS. Then, by superimposing exposure from each induced radionuclide, external immersion irradiation dose to medical staff from activated air was obtained. In this study, concentration of each radionuclide in air was compared with corresponding derived air concentration (DAC) limits.

The annual effective dose from external exposure caused by activated air is calculated as:

$$E_{air,ext} = T \times C_i \times DCF_{air,ext} \times \frac{1 - e^{-\lambda_i' t}}{\lambda_i'} \quad (1)$$

where $E_{air,ext}$ is annual effective dose from external exposure (Sv/a), T is annual working time of medical staff (h), C_i is radionuclide activity (Bq/m^3), and $DCF_{air,ext}$ is air immersion external radiation dose conversion factor ((Sv/s)/(Bq/m^3)). Because the treatment room has an exhaust system, radionuclide decay constant was corrected for this dynamic situation to λ_i':

$$\lambda_i' = \lambda_i + \frac{v}{V} \quad (2)$$

where λ_i is decay constant of radionuclide i (s^{-1}), v is exhaust air velocity (exhaust rate of Treatment Room 2 is 1.25 m^3/s or 4500 m^3/h), and V is room

volume. Waiting time t_w (min) for medical staff to enter after beam stopping and stay time t (min) per entry were introduced, modifying Eq. (1) to:

$$E_{air,ext} = N \times T \times C_i \times DCF_{air,ext} \times \frac{e^{-\lambda_i' t_w}(1 - e^{-\lambda_i' t})}{\lambda_i'}$$

(3)

where N is number of times medical staff enter treatment room per year (5000 per year, or 20 per day).

Annual effective dose from inhalation of air containing radionuclides (Sv/a) is estimated as:

$$E_{air,int} = C_i \times DCF_{inh} \times B$$

(4)

where C_i is inhaled air nuclide concentration (Bq/m^3), DCF_{inh} is inhalation dose conversion factor (Sv/Bq), and B is annual air breathed volume (m^3, calculated at 20 L/min). This calculation does not consider radionuclide decay in air during treatment room stay, using activity concentration upon entry to obtain a conservative inhalation internal irradiation annual effective dose.

2.3.2 Calculation of Dose to Family Members from Activated Phantom

To evaluate dose to patients' family members, the following formula was applied:

$$D_{family} = \int_{t_1}^{t_2} \dot{D}_\gamma(t) dt$$

(5)

where $\dot{D}_\gamma(t)$ is gamma-ray dose rate 30 cm from water phantom surface. The following scenario was assumed: patient leaves treatment room 2 min after irradiation ends, and family member attends for 2 h. Therefore, t_1 is 2 min and t_2 is 2 h. Patients receiving CIRT typically undergo 20–30 fractions maximum. Total exposure was conservatively obtained by multiplying integrated value of Eq. (5) by 30 [25].

2.3.3 Exemption Criteria

If radionuclide activity is less than its exemption value, it is considered exempt. If a substance contains multiple radionuclides and the sum of activity ratios to respective exemption values is less than one, the substance is also exempt. In other words, we must determine whether:

$$\sum_i \frac{A_i}{A_{exempt,i}} < 1$$

(6)

Exempt activities of radionuclides ($A_{exempt,i}$) can be found in GB18871-2002. This study roughly determined material activation degree by calculating whether the sum of ratios satisfied Eq. (6) [26].

3 Results and Discussion

This study evaluated three aspects of induced radioactivity in the treatment room: air activation, phantom activation, and beamline component activation. After treatment, medical staff must enter for further operations. Activated air causes external immersion irradiation, while inhaled activated air causes internal irradiation. We estimated occupational exposures for both components under different waiting and residence times and compared them with national standards. Patients' families might also receive additional radiation from patient activation after treatment, so we estimated this risk and compared it with standards. Equipment activation degree guides decommissioning, so we performed exemption evaluation of beamline components. This study provides reference for treatment and disposal of beamline equipment after treatment room dismantling, along with our recommendations.

3.1.1 Overview of Air Activation

As mentioned in Section 2, nine measurement points were established to reflect spatial distribution and temporal variation of induced radiation dose rate. Figure 2 [Figure 2: see original paper] illustrates dose rates at each point at various times: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, and 30 min after irradiation. Dose rates along the beam direction were significantly higher than corresponding points in the 45° direction and perpendicular direction. The latter two orientations showed similar dose rates, except at 50 cm where the 45° direction dose rate was significantly higher. Dose rate decreased with distance, though this trend was less obvious in the 0° beam direction compared to other directions. These observations coincide with particle flux distribution in the treatment room.

The dose rate temporal trend was consistent with distance trends, decreasing over time. Furthermore, dose rates in the 45° and 90° directions decreased sharply within 1 min after beam-off then slowed. Many radionuclides are generated by nuclear reactions during irradiation, most being short-lived with half-lives under 1 min. Due to low heavy ion scattering, few particles exist in non-beam directions, resulting in low nuclear reaction probability. The effect of short-lived radionuclides on induced radiation dose rate was considerably greater in non-beam directions than in the beam direction. In the 0° beam direction, dose rate time course was slower than in other directions, as shown in Fig. 2.

Overall, induced radioactivity distribution in the treatment room was non-uniform, with higher dose-rate areas of residual radiation field concentrated along the beam direction. Based on simulation data trends and radiological protection optimization principles, medical staff should avoid high dose-rate areas near the isocenter along the beam direction when entering the treatment room.

3.1.2 Annual Effective Dose to Medical Staff from Air Activation

Activity concentrations of each radionuclide at irradiation end were first compared with DAC limits. DAC is the radionuclide concentration limit based on annual intake limit (ALI), indicating occupational exposure should comply with dose equivalent limit regulations [26,27]. In this simulation, each nuclide's activity concentration was lower than corresponding DAC values. This simulation did not consider indoor ventilation during treatment, obtaining relatively conservative nuclide activity concentrations. The fact that radionuclide concentrations were below DAC values demonstrates that radionuclide distribution in treatment room air after CIRT complies with radiation protection regulations.

Table 2 . Radioactivity of Main Nuclides and Their Corresponding DAC Values

Nuclide	$DCF_{air,ext}$ (Sv/s)/(Bq/m^3)	DCF_{inh} (Sv/Bq)	Half-life (s)	Activity Concentration (Bq/m^3)	DAC (Bq/m^3)
	2.7778$×10^{3}$	1.0269$×10^{-2}$	-1.8000$×10^{-11}$	8.00$×10^{5}$	2.7779$×10^{3}$
	3.7382$×10^{-2}	2.7400$×10^{-15}$	-5.2000$×10^{-11}$	3.00$×10^{5}$	3.3445$×10^{3}$
	2.9122$×10^{2}$	7.9100$×10^{-14}$	-2.2000$×10^{-12}$	1.00$×10^{7}$	2.7778$×10^{3}$
	1.4547$×10^{-4}$	2.4300$×10^{-16}$	-6.5000$×10^{-12}$	6.9371$×10^{3}$	2.8093$×10^{3}$
	8.6800$×10^{-14}$	8.4500$×10^{-3}	3.3413$×10^{-13}	1.00$×10^{-13}$	7.00$×10^{4}$
Cl-38	3.0880$×10^{3}$	2.0354$×10^{-3}$	-1.9400$×10^{-13}$	7.0300$×10^{-11}$	6.00$×10^{5}$
Cl-39	2.9856$×10^{3}$	1.5180$×10^{-1}$	-1.3600$×10^{-13}$	7.6000$×10^{-11}$	8.00$×10^{5}$
Ar-41	2.8832$×10^{3}$	1.0100$×10^{-13}$			

Table 3 . Annual Effective Dose to Medical Staff from Main Nuclides Activated in Indoor Air

Waiting Time (min)	Residence Time (min)	Annual Effective Dose External Radiation (mSv/a)	Annual Effective Dose Internal Radiation (mSv/a)
		1.695$×10^{-4}$	3.390$×10^{-4}$
		5.085$×10^{-4}$	6.240$×10^{-5}$
		1.248$×10^{-4}$	1.872$×10^{-4}$
		8.500$×10^{-6}$	1.690$×10^{-5}$
		2.540$×10^{-5}$	

Using the formulas presented in Section 2, annual effective doses from external immersion and internal inhalation caused by air activation were calculated and listed in Table 3. Medical staff entry frequency was assumed to be 5000 times per year (20 per day). Internal inhalation dose values were three orders of magnitude smaller than external radiation doses, even under conservative calculation conditions. Therefore, we conclude that dose from activated air principally originates from external irradiation. If staff enter immediately after treatment, annual effective external radiation dose from air activation is 0.379–0.4107 mSv; at 5 and 10 min after beam-off, this reduces to 0.0948–0.1051 mSv and 0.0092–0.0104 mSv, respectively. According to Chinese Standard GB18871-2002, the occupational annual dose limit is 20 mSv [24]. None of these values exceed professional personal dose limits in basic standards.

Overall, external exposure dose is important when calculating annual effective dose from air activation. Estimation results show that delaying entry after radiotherapy reduces annual effective external immersion dose to medical staff. Therefore, radiation protection optimization principles recommend an appropriate delay period after radiotherapy before staff enter the treatment room.

3.2 Estimation of Exposure to Patients' Family Members from Activated Phantom

Patient activation was not traditionally concerning with older photon-based treatments but is increasingly relevant as high-energy ion treatments have gained prominence because spallation products and secondary neutron reactions result in notable activation [16]. This study estimated patient activation and possible additional dose to relatives after CIRT based on phantom activation in simulation.

Many radionuclides were generated within the phantom during simulation, most being short-lived nuclides existing only during beam irradiation before decaying. After therapeutic irradiation, main phantom nuclides were O-15, O-14, C-11, N-13, and C-10, originating mainly from O-16 spallation by high-energy neutrons. After rapid decay of O-15, O-14, and C-10, C-11 and N-13 became dominant approximately 10 min after irradiation. Other nuclides increased proportionally after 20 min, as shown in Fig. 3 [Figure 3: see original paper], mainly long-lived nuclides such as H-3 and Be-7.

Table 4 . Main Radionuclides in Phantom After Irradiation

Nuclide	Half-life (s)	Decay Mode
	1.22$×10^{2}$	EC, β^+
	7.06$×10^{1}$	EC, β^+
	1.22$×10^{3}$	EC, β^+
	5.98$×10^{2}$	EC, β^+
	1.93$×10^{1}$	EC, β^+
	3.89$×10^{8}$	EC, β^+
	4.60$×10^{6}$	

As shown in Table 4, EC and β^+ decay were dominant modes, with positron annihilation from β^+ decay emitting photons. Because beta rays are less penetrating, only secondary photon dose from material activation was considered for water phantom activation. Calculated photon spectra from irradiated phantom were used as input source term for secondary-stage calculation to assess dose from activated materials. Time-dependent changes in secondary photon dose rate from phantom material activation are shown in Fig. 4 [Figure 4: see original paper]. When radioactivated by carbon ions, the phantom emitted radiation from its center into surroundings. Secondary photon dose decreased with distance from phantom. The treatment room maze structure provides good shielding, significantly reducing dose rates at maze entrance and corridor. However, no similar shielding exists between family members and patients after CIRT, and photon dose-rate levels around patients are relatively high immediately after exposure. Therefore, estimating additional dose to family members from activation of CIRT patients is necessary.

Family exposure was calculated as 40 Sv for HIMM using Eq. (5). This is nearly double the 23.5 Sv for HIMAC (Heavy Ion Medical Accelerator in Chiba) at NIRS and 20.8 Sv for Hyogo Ion Beam Medical Center (HIBMC) [25], primarily because we adopted maximum HIMM beam parameters for conservative data. Most radioactive nuclides produced in phantoms have very short half-lives, so prolonged attendance by family members hardly increases exposure. In ICRP Publication 103, this exposure type is classified as medical exposure, making public dose limits unsuitable [28]. However, our calculated family exposure is far below the 1 mSv/a public dose limit, indicating minimal impact on patients' families.

Fig. 5 [Figure 5: see original paper]. Variation in Secondary Photon Dose Rate with Time at Measurement Point

3.3 Material Activation Analysis

Primary and secondary particles react with beamline components to generate large amounts of radionuclides, activating materials. Assessing beamline component activation levels is important for guiding equipment decommissioning. To

simplify simulation, simple geometries replaced complex beamline components, with specific parameters listed in Table 5 .

Components were divided into fixed and non-fixed categories. For fixed components (PC, RF, MLC), continuous 30-year exposure at maximum flux intensity was set. For patient-specific range shifters and compensators, only activation after one patient session was considered: 20 min continuous irradiation followed by 24 h cooling, repeated 30 times per patient session.

For fixed components, many radionuclides were generated after irradiation, particularly in MLC. Many were short-lived but less important for radiation protection. Therefore, considering half-life and activity together, meaningful radionuclides were organized in tables. RS and compensator produced considerably fewer radionuclides.

Table 5. Material of Each Equipment in the Beamline

Component	Density (g/cm^3)	Material	Open Field (cm^2)
PC	18.230	Cu 5% W 95%	15 × 15
RF			15 × 15
MLC			
Compensator		Polyethylene	

Table 6 . Main Nuclides of the PC

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Ni-63	4.06$×10^{5}$	1.00$×10^{8}$	4.06$×10^{-3}$	3.19$×10^{9}$
Co-60	4.66$×10^{6}$	1.00$×10^{9}$	4.66$×10^{-3}$	3.89$×10^{8}$
Fe-55	9.61$×10^{5}$	1.00$×10^{5}$	9.17$×10^{-1}$	1.66$×10^{8}$
Na-22	9.17$×10^{5}$	1.00$×10^{6}$	5.08$×10^{-2}$	8.66$×10^{7}$
Mn-54	5.08$×10^{4}$	1.00$×10^{6}$	8.59$×10^{-1}$	8.21$×10^{7}$
Co-57	8.59$×10^{5}$	1.00$×10^{6}$	1.29$×10^{-1}$	2.70$×10^{7}$
Zn-65	1.06$×10^{6}$	1.00$×10^{6}$	8.52$×10^{-3}$	2.35$×10^{7}$
Ca-45	1.29$×10^{5}$	1.00$×10^{6}$	1.19$×10^{-3}$	2.11$×10^{7}$
Sc-46	8.52$×10^{4}$	1.00$×10^{7}$	2.32$×10^{-1}$	1.41$×10^{7}$
Co-56	1.19$×10^{5}$	1.00$×10^{8}$	1.43$×10^{-2}$	7.56$×10^{6}$
Co-58	2.32$×10^{5}$	1.00$×10^{6}$	1.28$×10^{-1}$	7.24$×10^{6}$
Fe-59	2.61$×10^{5}$	1.00$×10^{5}$	1.15$×10^{-3}$	6.67$×10^{6}$
Ar-37	1.43$×10^{6}$	1.00$×10^{6}$	6.08$×10^{-2}$	6.12$×10^{6}$
Cr-51	1.43$×10^{5}$	1.00$×10^{7}$	1.36$×10^{-3}$	4.60$×10^{6}$
Mn-52	1.28$×10^{5}$	1.00$×10^{6}$	1.19$×10^{-2}$	3.84$×10^{6}$
Ca-47	1.15$×10^{5}$	1.00$×10^{8}$	6.08$×10^{-2}$	3.03$×10^{6}$
Sc-47	6.08$×10^{5}$	1.00$×10^{7}$	1.36$×10^{-3}$	2.39$×10^{6}$
Sc-48	1.36$×10^{5}$	1.00$×10^{8}$	1.19$×10^{-2}$	2.19$×10^{6}$
Co-55	1.28$×10^{5}$	1.00$×10^{5}$	2.65$×10^{-1}$	1.38$×10^{6}$

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Na-24	1.19$×10^{4}$	1.00$×10^{5}$	1.84$×10^{-1}$	1.23$×10^{6}$
Cu-64	1.84$×10^{5}$	1.00$×10^{6}$	6.80$×10^{-1}$	4.83$×10^{5}$
Fe-52	6.80$×10^{4}$	1.00$×10^{5}$	6.53$×10^{-2}$	3.92$×10^{5}$
Si-31	6.53$×10^{4}$	1.00$×10^{6}$	4.80$×10^{-2}$	2.89$×10^{5}$
Mn-56	4.80$×10^{4}$	1.00$×10^{6}$	5.71$×10^{-1}$	1.57$×10^{5}$
Ni-65	5.71$×10^{4}$	1.00$×10^{5}$	1.28$×10^{-1}$	8.03$×10^{4}$
Ar-41	3.60$×10^{6}$	1.00$×10^{6}$	5.19$×10^{-3}$	6.31$×10^{4}$
Co-61	1.28$×10^{5}$	1.00$×10^{6}$	6.03$×10^{-2}$	5.40$×10^{4}$
Mn-51	5.19$×10^{3}$	1.00$×10^{6}$	2.38$×10^{-1}$	4.57$×10^{4}$
Cl-38	6.03$×10^{4}$	1.00$×10^{5}$	1.69$×10^{-1}$	4.45$×10^{4}$
Mn-52m	2.38$×10^{5}$	1.00$×10^{6}$	6.99$×10^{-2}$	2.98$×10^{4}$
	1.69$×10^{5}$	1.00$×10^{6}$	2.35$×10^{-2}$	9.44$×10^{3}$
	6.99$×10^{4}$	1.00$×10^{6}$	5.12$×10^{-1}$	9.28$×10^{3}$
	2.35$×10^{4}$	1.00$×10^{5}$	4.51$×10^{-1}$	9.06$×10^{3}$
	5.12$×10^{5}$	1.00$×10^{5}$	5.74$×10^{-1}$	6.59$×10^{3}$
	4.51$×10^{4}$	1.00$×10^{5}$	5.32$×10^{-2}$	6.58$×10^{3}$
	5.74$×10^{4}$	1.00$×10^{9}$	1.83$×10^{-5}$	5.94$×10^{3}$
	5.32$×10^{3}$			2.77$×10^{3}$
	1.83$×10^{4}$			2.23$×10^{3}$
				1.27$×10^{3}$
				1.22$×10^{2}$

Table 7 . Main Nuclides of the MLC

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Ni-63	2.64$×10^{5}$	1.00$×10^{8}$	2.64$×10^{-3}$	3.19$×10^{9}$
Co-60	1.82$×10^{6}$	1.00$×10^{9}$	1.82$×10^{-3}$	3.89$×10^{8}$
Fe-55	5.81$×10^{5}$	1.00$×10^{5}$	4.91$×10^{-1}$	1.66$×10^{8}$
Na-22	4.91$×10^{5}$	1.00$×10^{6}$	4.68$×10^{-3}$	8.66$×10^{7}$
Mn-54	4.68$×10^{3}$	1.00$×10^{6}$	4.48$×10^{-1}$	8.21$×10^{7}$
Co-57	4.48$×10^{5}$	1.00$×10^{6}$	6.03$×10^{-1}$	2.70$×10^{7}$
Zn-65	6.03$×10^{5}$	1.00$×10^{6}$	7.36$×10^{-2}$	2.35$×10^{7}$
Ca-45	7.36$×10^{4}$	1.00$×10^{6}$	2.91$×10^{-3}$	2.11$×10^{7}$
Ce-139	2.91$×10^{4}$	1.00$×10^{7}$	1.96$×10^{-3}$	1.41$×10^{7}$
W-181	1.96$×10^{3}$	1.00$×10^{6}$	3.08$×10^{-2}$	1.19$×10^{7}$
Ta-182	3.08$×10^{5}$	1.00$×10^{7}$	2.63$×10^{-4}$	1.05$×10^{7}$
Sc-46	6.47$×10^{4}$	1.00$×10^{8}$	8.59$×10^{-2}$	9.91$×10^{6}$
Co-56	2.63$×10^{4}$	1.00$×10^{6}$	1.37$×10^{-2}$	7.56$×10^{6}$
W-185	8.59$×10^{4}$	1.00$×10^{5}$	2.49$×10^{-2}$	7.24$×10^{6}$
Co-58	1.37$×10^{5}$	1.00$×10^{7}$	8.46$×10^{-1}$	6.67$×10^{6}$
Fe-59	2.49$×10^{5}$	1.00$×10^{6}$	1.80$×10^{-2}$	2.49$×10^{5}$
Cr-51	8.46$×10^{5}$	1.00$×10^{7}$	7.43$×10^{-2}$	6.12$×10^{6}$

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Mn-52	1.80$×10^{5}$	1.00$×10^{6}$	2.80$×10^{-2}$	4.60$×10^{6}$
Sc-47	7.43$×10^{4}$	1.00$×10^{7}$	3.19$×10^{-1}$	3.84$×10^{6}$
Sc-48	2.80$×10^{5}$	1.00$×10^{5}$	9.67$×10^{-1}$	2.39$×10^{6}$
W-187	1.03$×10^{5}$	1.00$×10^{5}$	2.63$×10^{-1}$	1.38$×10^{6}$
Co-55	3.19$×10^{4}$	1.00$×10^{5}$	2.57$×10^{-2}$	1.23$×10^{6}$
Na-24	9.67$×10^{4}$	1.00$×10^{6}$	2.02$×10^{-2}$	4.83$×10^{5}$
Cu-64	7.05$×10^{4}$	1.00$×10^{6}$	2.27$×10^{-2}$	2.89$×10^{5}$
Si-31	2.63$×10^{4}$	1.00$×10^{5}$	5.52$×10^{-2}$	1.57$×10^{5}$
Mn-56	2.57$×10^{4}$	1.00$×10^{6}$	3.79$×10^{-2}$	8.64$×10^{4}$
Ni-65	2.02$×10^{4}$	1.00$×10^{6}$	1.04$×10^{-2}$	8.03$×10^{4}$
Co-61	2.27$×10^{4}$	1.00$×10^{6}$	1.03$×10^{-1}$	6.31$×10^{4}$
Mn-51	5.52$×10^{3}$	1.00$×10^{5}$	4.81$×10^{-3}$	5.40$×10^{4}$
Cl-38	2.22$×10^{6}$	1.00$×10^{6}$	3.29$×10^{-1}$	4.57$×10^{4}$
	3.79$×10^{4}$	1.00$×10^{6}$	1.95$×10^{-1}$	4.45$×10^{4}$
	1.04$×10^{4}$	1.00$×10^{5}$	1.40$×10^{-1}$	9.44$×10^{3}$
	1.26$×10^{5}$	1.00$×10^{6}$		9.28$×10^{3}$
	1.03$×10^{5}$	1.00$×10^{6}$		9.06$×10^{3}$
	4.81$×10^{3}$	1.00$×10^{5}$		6.59$×10^{3}$
	3.29$×10^{5}$	1.00$×10^{6}$		5.94$×10^{3}$
	1.95$×10^{4}$	1.00$×10^{5}$		2.77$×10^{3}$
	1.40$×10^{4}$	1.00$×10^{5}$		2.23$×10^{3}$

Table 8 . Main Nuclides of the RF

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Na-22	3.23$×10^{6}$	1.00$×10^{9}$	3.23$×10^{-3}$	3.89$×10^{8}$
Na-24	2.99$×10^{5}$	1.00$×10^{7}$	2.99$×10^{-2}$	4.60$×10^{6}$
	2.60$×10^{2}$	1.00$×10^{7}$	2.60$×10^{-5}$	1.80$×10^{11}$
	2.01$×10^{5}$	1.00$×10^{9}$	2.01$×10^{-4}$	1.22$×10^{2}$
	6.52$×10^{5}$	1.00$×10^{6}$	6.52$×10^{-1}$	6.59$×10^{3}$
	6.92$×10^{5}$	1.00$×10^{6}$	6.92$×10^{-1}$	8.21$×10^{7}$
Si-31	7.39$×10^{5}$	1.00$×10^{5}$	3.00$×10^{-5}$	5.40$×10^{4}$
	3.00$×10^{1}$	1.00$×10^{6}$	4.99$×10^{-4}$	9.44$×10^{3}$
	4.99$×10^{1}$	1.00$×10^{5}$		1.23$×10^{6}$

Table 9 . Main Nuclides of the RS

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Na-22	2.23$×10^{2}$	1.00$×10^{9}$	2.23$×10^{-7}$	3.89$×10^{8}$
Si-31	4.02$×10^{3}$	1.00$×10^{7}$	4.02$×10^{-4}$	4.60$×10^{6}$
	1.72$×10^{4}$	1.00$×10^{7}$	1.65$×10^{-9}$	1.22$×10^{3}$

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
	1.65$×10^{-2}$	1.00$×10^{9}$	2.31$×10^{-21}$	1.80$×10^{11}$
	4.55$×10^{1}$	1.00$×10^{6}$	1.34$×10^{-4}$	5.98$×10^{2}$
	2.31$×10^{-12}$	1.00$×10^{6}$	2.41$×10^{-9}$	1.22$×10^{2}$
	1.34$×10^{2}$	1.00$×10^{5}$	6.92$×10^{-22}$	6.59$×10^{3}$
	2.41$×10^{-3}$	1.00$×10^{6}$		8.21$×10^{7}$
	6.92$×10^{-17}$	1.00$×10^{5}$		9.44$×10^{3}$

Table 10 . Main Nuclides of the Compensator

Nuclide	Activity (Bq)	Exempt (Bq)	Activity/Exempt	Half-life (s)
Be-10	7.23$×10^{8}$	1.00$×10^{9}$	7.23$×10^{-1}$	3.89$×10^{8}$
	1.36$×10^{4}$	1.00$×10^{7}$	3.18$×10^{-5}$	4.60$×10^{6}$
	6.70$×10^{-12}$	1.00$×10^{7}$	6.23$×10^{3}$	4.77$×10^{13}$
	7.97$×10^{-25}$	1.00$×10^{9}$	6.73$×10^{-10}$	1.22$×10^{3}$
	1.11$×10^{-9}$	1.00$×10^{9}$	7.23$×10^{1}$	1.80$×10^{11}$
	6.73$×10^{-10}$	1.00$×10^{8}$	1.36$×10^{3}$	5.98$×10^{2}$
	7.23$×10^{1}$	1.00$×10^{9}$	3.31$×10^{-1}$	1.22$×10^{2}$
	1.36$×10^{3}$	1.00$×10^{9}$	7.97$×10^{-16}$	6.59$×10^{3}$
	3.18$×10^{-5}$	1.00$×10^{8}$	6.73$×10^{-2}$	2.19$×10^{6}$
	6.23$×10^{3}$			

For PC, MLC, and RF, the sum of ratios of individual nuclides to their exemption values was considerably greater than 1. Therefore, fixed beamline components after treatment room decommissioning must be stored in isolation and disposed of until radioactivity reaches exempt levels. RS and compensator produced weak activity and fewer long-lived nuclides because they are low atomic number materials. Their activation levels after one patient session were exempt. However, considering the ALARA principle, we still recommend isolation after treatment.

4 Conclusion

Investigation of non-therapeutic radiation is vital for better radiotherapy efficacy. In a previous study, we analyzed secondary neutron doses under passive beam delivery and applied an analytical model to predict ambient dose equivalent [29]. This study comprehensively analyzed induced radioactivity, enriching understanding of non-therapeutic radiation in CIRT. Based on MC particle transport simulation software PHITS, we evaluated activation of air, phantom, and beamline components in a CIRT treatment room. For air activation, we calculated medical staff external immersion and internal inhalation exposures. For phantom activation, we estimated additional dose to patients' families from

secondary photons. For component material activation, we evaluated exemption status. The following conclusions were drawn:

1. After beam-off, high dose-rate areas of induced radioactivity were mainly located upstream of beam direction near phantom. Medical staff should avoid these areas when entering to reduce radiation hazards.

2. Annual effective dose from air activation does not exceed professional personal dose limits in basic standards, with air immersion external radiation as the main source. Additionally, appropriate delay before entering after radiotherapy is recommended.

3. Treatment room maze structure provides good shielding, significantly reducing secondary photon dose rates from phantom activation at maze entrance and corridor. Dose rate near phantom was high immediately after beam-off, then decreased roughly exponentially. Additional dose to patients' families from secondary photons of current treatment fraction was estimated at approximately 40 Sv, having minimal impact.

4. Beamline components generate large amounts of radionuclides after nuclear reactions. High atomic number materials produce high induced radioactivity and long-lived nuclides. PC, RF, and MLC induced radioactivity exceeds exempt levels after retirement, requiring isolation. RS and compensator can reach exempt levels after one patient session but should still be separated.

Additional radiation from induced radioactivity in Treatment Room 2 of HIMM is below legal limits. We made radiation protection recommendations based on analysis, applicable to other CIRT centers.

Simulation limitations include simplified beamline model and neglected devices such as patient couch. Ventilation during irradiation was also not considered. Nevertheless, this study provides a framework for other CIRT treatment room induced radioactivity studies, with experimental measurements planned for future work.

In summary, this study provides references for assessing induced radioactivity levels in CIRT treatment rooms and radiation protection recommendations for staff and equipment decommissioning. With CIRT popularization in China, this study may help centers address induced radioactivity protection. For new techniques such as FLASH, multi-ion combined therapy, and arc therapy, re-evaluating induced radioactivity levels is important. This paper's methods also provide guidance for induced radioactivity studies under these new techniques to facilitate clinical application.

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Note: Figure translations are in progress. See original paper for figures.