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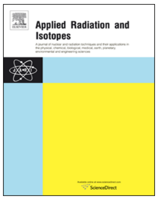

Study on patient-induced radioactivity during proton treatment in hengjian proton medical facility

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HIGHLIGHTS

- A detailed study on patient-induced radioactivity was conducted by adopting Monte Carlo code FLUKA and activation formula.
- New formulas for calculating the activity build-up process of periodic irradiation were derived and extensively studied.
- Patient induced radioactivity, which has been ignored for years, is confirmed as a vital factor for radiation protection.
- The induced radioactivity from single short-time treatment and long-time running (saturation) were studied and compared.
- Some suggestions on how to reduce the hazard of patient's induced radioactivity were given.

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ABSTRACT

At present, increasingly more proton medical facilities have been established globally for better curative effect and less side effect in tumor treatment. Compared with electron and photon, proton delivers more energy and dose at its end of range (Bragg peak), and has less lateral scattering for its much larger mass. However, proton is much easier to produce neutron and induced radioactivity, which makes radiation protection for proton accelerators more difficult than for electron accelerators. This study focuses on the problem of patient-induced radioactivity during proton treatment, which has been ignored for years. However, we confirmed it is a vital factor for radiation protection to both patient escort and positioning technician, by FLUKA's simulation and activation formula calculation of Hengjian Proton Medical Facility (HJPMF), whose energy ranges from 130 to 230 MeV. Furthermore, new formulas for calculating the activity buildup process of periodic irradiation were derived and used to study the relationship between saturation degree and half-life of nuclides. Finally, suggestions are put forward to lessen the radiation hazard from patient-induced radioactivity.

1. Introduction

At present, increasingly more proton medical facilities have been established globally for better curative effect and less side effect in tumor treatment. Compared with photon and electron, proton delivers more energy and dose at its end of range (Bragg peak), and has less lateral scattering for its much larger mass. However, proton is much easier to produce neutron and induced radioactivity, when energy is scaled up to several million electron volts, which makes radiation protection for proton accelerators more difficult than for electron accelerators. This study focuses on the problem of patient-induced radioactivity during proton treatment, which has been ignored for years. However, it has been extensively studied by the author in the process of radiation protection design for Hengjian Proton Medical Facility (HJPMF).

HJPMF is planned to be built in Guangzhou, Guangdong, China, with its proton accelerator named C230 cyclotron bought from IBA (one of the famous proton medical facility producers). As shown in Fig. 1, in HJPMF, degrader, collimator, and slits form the energy selection system (ESS) and both cyclotron and ESS are located in the cyclotron room. First, 230-MeV proton beam is extracted from the C230 cyclotron, then the beam's energy is degraded from

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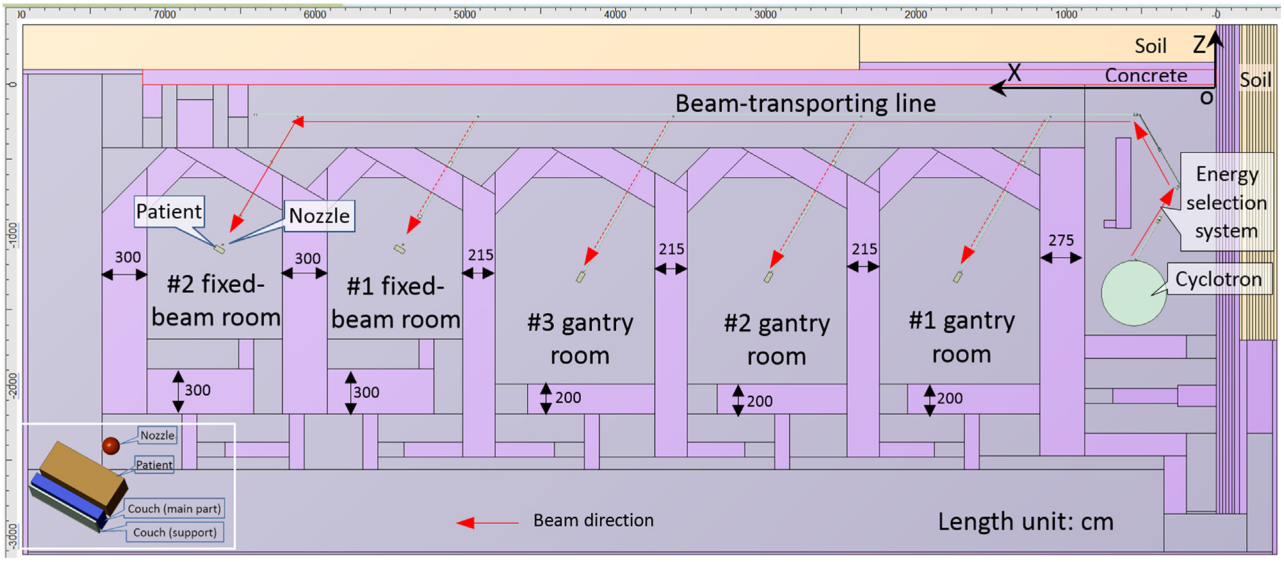

Fig. 1. Structure of HJPMF at its beam plane, plotted using SimpleGeo (details of components distribution in fixed-beam room shown at the lower left corner) (Theis et al., 2006).

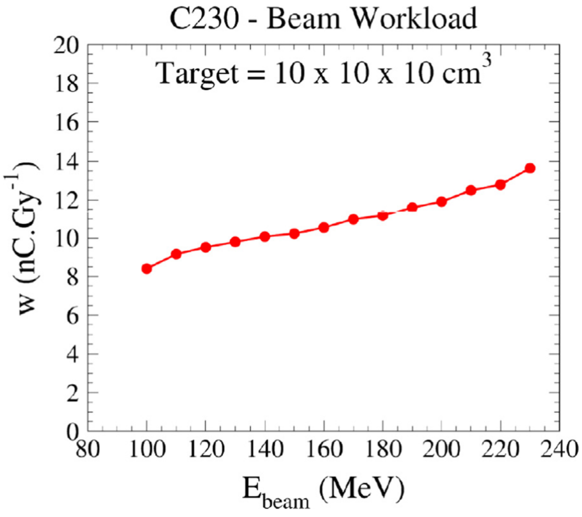

Fig. 2. Beam workload as a function of beam energy to deliver 1-Gy dose in a 1-L water target volume (Stichelbaut, 2014a, b).

Table 1
Beam energy, workload weight, IBA workload and HJPMF workload obtained with IBA case mix (Stichelbaut, 2014b).

Energy (MeV)	230	210	180	160	130	Total
IBA workload per room (nA.h)	37.25	29.59	26.08	66.34	52.5	211.76
Workload weight	0.176	0.140	0.123	0.313	0.248	1.000
HJPMF workload per room (nA.h)	88.00	70.00	61.50	156.50	124.00	500.00

230 MeV to a certain energy between 130 and 230 MeV by the degrader. The beam is then collimated and size-reduced by the collimator and slits. Afterward, the beam is transported to the beam-transporting line (BTL), turned to the treatment room, and allowed to reach the target (patient) (Stichelbaut, 2014a). Only pencil beam scanning (PBS) mode will be adopted for treatment in HJPMF, to avoid beam loss at nozzle and aperture. Only two source terms need to be considered from BTL to patient: beam line loss at beam pipe with most 0.106 nA at 230 MeV and beam point loss at patient with most 1.66 nA at 230 MeV. In HJPMF, five treatment rooms are planned, including three gantry rooms and two fixed-beam rooms. During treatment, the beam transports from BTL to one of the treatment rooms; the other rooms have no beam and are prepared for patient positioning. The proton energy is also changeable to adapt to different tumor depths. In IBA's treatment assumption (Stichelbaut, 2014a, b), 350 patients were treated every year and in each room, and 4800 h per year are spent for treatment (16 h/day, 6 days/week, 50 weeks/year). Fig. 2 shows the beam workload (expressed in nanocoulombs) needed to deliver 1-Gy dose in 1 L of water (note: patient can be replaced by water phantom). IBA also listed the possible clinical indications through the running experiences from its approximately 20 proton treatment centers (Stichelbaut, 2014b). Combining the workload with the possible clinical indications, and according to the five energy points used in HJPMF, IBA converted the case mix into annual workloads, as shown in rows 1–3 in Table 1. Referring to these IBA's treatment assumptions and the five energy points' workload weight presented in Table 1, HJPMF established its treatment annual workloads as shown in Table 2 and the corresponding energy workload as shown in Table 1.

According to Tables 1 and 2, and combined with the transporting efficiency in ref. Stichelbaut (2014a), we obtained all the source terms in HJPMF, whose source terms in each treatment room are shown in Table 3. Some notes in our calculation are also shown in Table 3.

The dose-governed target values for HJPMF are 5 and 0.1 mSv/a for radiation worker and public, respectively. The dose rate limit is < 2.5 μSv/h in the working place for shielding design, and the designed structure is shown in Fig. 1.

2. Calculation and analysis

2.1. Geometrical model and calculation method

In order to calculate induced radioactivity in the treatment room of HJPMF, Monte Carlo code FLUKA (Ferrari et al., 2011; Bohlen et al., 2014) was adopted to simulate the beam loss and transport process. The geometrical model shown in Fig. 1 was plotted using SimpleGeo (Theis et al., 2006). In order to simplify and consider the components' activation, all the magnets and other components were omitted, except beam pipe, nozzle, patient, and walls. The beam pipe was constructed as a cylindrical shell made of pure iron material, with inner and outer radii 4 and