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ORIGINAL PAPER

Assessment of the staff absorbed dose related to cyclotron operation and service in the production of ^{18}F radiopharmaceuticals

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Abstract. Cyclotron accelerators are used to produce medical radioisotopes. One of the most important problems which may be encountered is malfunction of a part of the target or beam line which requires stopping of the bombardment and making a repair. The decision about doing the repair depends on the whole body dose rate in a target room. In this work, dosimetric conditions related to the production of ^{18}FDG radiopharmaceutical were simulated by the Monte Carlo (MC) method. Independently, the dose rates were measured by 7 ICRU spherical body phantoms placed inside the liquid target room and the maze of the cyclotron. The radiation dose rate inside the target room depends on the duration of the bombardment and the time passed after stopping the bombardment. The correlation between duration of the bombardment and required time after stopping the bombardment to reach the absorbed dose rate less than 25 μSv/h, was calculated for the presence and absence of the irradiated target. The results showed that the repair can be started immediately after stopping of the proton bombardment only if the target has been ejected from the target room and the duration of bombardment has not taken more than 10 min.

Key words: staff dosimetry • Monte Carlo (MC) simulation • ^{18}F production • cyclotron • induced radioactivity • liquid target

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Introduction

Positron emission tomography (PET) is a non-invasive medical imaging technology that can generate high-resolution images of physiologic functions with clinical application for oncology, cardiology and neurology [10]. ^{18}F is one of the most important isotopes used in nuclear medicine and large quantities are produced for the sake of diagnostics, especially for production of the ^{18}FDG radiopharmaceutical [1]. The ^{18}F-FDG compound is an important positron-emitting tracer for positron emission tomography that is produced by the Cyclotron Department of Agricultural, Medical and Industrial Research Schools (AMIRS) in Iran. The ^{18}F radioisotope was produced via the ^{18}O (p,n) ^{18}F reaction induced by a 18 MeV and 16 μA proton beam of the cyclotron on an enriched $H_2{}^{18}O$ target. When a cyclotron operates to produce the radioactive nuclide, secondary radiations such as neutrons and γ-rays are induced, too [8]. Scattered proton particles, secondary neutrons and γ-rays may cause nuclear reaction in collision with the target room components and concrete walls. Entry to the liquid target room of the cyclotron during the bombardment is not allowed. So, to repair the malfunction, cyclotron staff can go into the cyclotron target room after the cyclotron shut down. In this situation, γ-rays from the residual radiation, contribute to the main radiation dose for the staff.

Several authors focused their attention on estimating the internal doses of patients and external doses of physicians as they perform injections of ^{18}F-FDG and do the acquisition in PET examination, but less discussion has been done about the absorbed doses of the cyclotron staff [3, 8]. M. J. Kuo *et al.* [8] estimated the radiation dose of personnel in the medical cyclotron centre by using thermoluminescent dosimeter (TLD). In this case, the ^{18}F-FDG compound was produced and the contributed dose from photons and neutrons inside the cyclotron target room during operation of the cyclotron was measured [8]. In another effort, personnel exposure from residual radiation has been presented by M. F. Moyers *et al.* [9], after shut down of an accelerator. In this case, the measurements were made with survey instruments around the synchrotron accelerator at the Loma Linda University and personnel dosimetry data during the maintenance were recorded [9].

In the previous studies the experimental results have been reported but they are very sensitive to the arrangement of a cyclotron centre and to the conditions of dosimetry evaluation. So, in this work, a cylindrical silver target body, aluminium case beam lines, an iron switching magnet, components of concrete walls of the vault and other equipment of the liquid target room, and also induced radioactivity of the target, were simulated by the Monte Carlo (MC) method. Then, the whole body absorbed dose of the cyclotron personnel due to residual radiation was calculated for different places of the liquid target room. This evaluation simulates the absorbed dose of staff during the repair after the emergency and routine cyclotron shutdown.

Materials and methods

In the Cyclotron Department of Iran the rubidium-81/krypton-81m generators and F-18 radiopharmaceuticals are produced in the same target room. Actually, to produce ^{18}F radioisotope the beam line and other equipment of the enriched $H_2{}^{18}O$ target are added to the krypton target room. Figure 1 shows the geometry of the target room including its multi-bend maze and locations of spherical dosimeters. In this case radioactivation can occur in the following components:

1. Cylindrical silver body of the liquid target – by protons scattered in the target and neutrons produced in the target.
2. Aluminum case of beam lines – by neutrons produced in the target and its body.
3. Iron switching magnet – by protons scattered and neutrons produced in the target, which exit from the target body.
4. Titanium windows set at the end of the beam line and at the front of the target – by protons accelerated in the cyclotron and neutrons produced in the target body.
5. Conical steel body of the krypton target – by scattered protons and secondary neutrons that exit from the target body.
6. In the surrounding walls of the target room and its maze – by protons scattered and neutrons produced in the target that exit from the target body.

Through the MC method, the average proton and neutron fluence rate spectra inside the enriched $H_2{}^{18}O$ target and for 6 cases mentioned above were calculated. Then, by using the Eqs. (1) and (2), with the obtained proton and neutron fluence data and the cross sections in the appropriate energy range, the produced radioisotopes were recognized and their activities were calculated.

$$A_0 = \sigma \varphi n (1 - e^{-\lambda T}) \tag{1}$$

$$A = A_0 e^{-\lambda t} \tag{2}$$

where: σ is the cross section of the reaction considered, φ is the fluence rate of particles (neutrons or protons), n is the total number of atoms in the component, λ is the decay constant of the induced radioactivity, T and t are the time of bombardment and waiting time after stopping of the bombardment, respectively [2]. Using the MC method, the whole body dose inside the spherical ICRU phantoms, which were placed at 100 cm height from the floor level, were evaluated. The ICRU sphere is a 30 cm diameter tissue equivalent sphere consisting of a material with a density of 1 g/cm^3 and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen [4, 6]. The geometry of the liquid target room and the positions of phantoms are shown in Fig. 1.

Results

The total proton fluence rate inside the enriched $H_2{}^{18}O$ target, obtained by the MC method, was

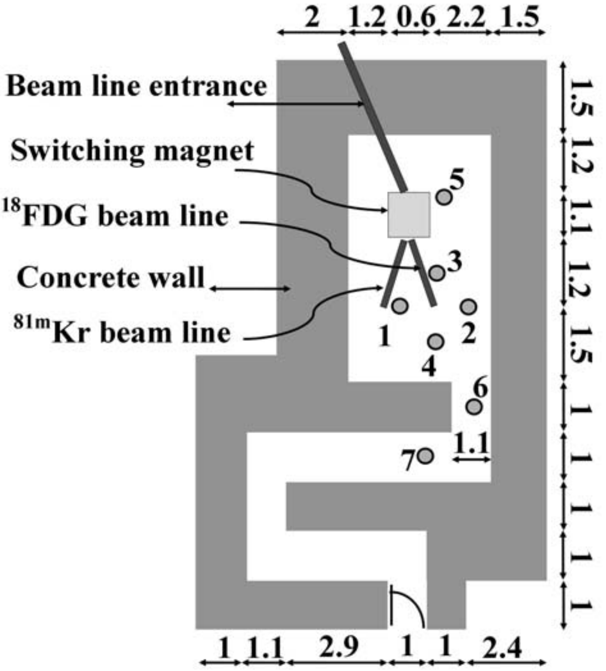

Fig. 1. Geometry of the target room including its multi-bend maze and locations of spherical dosimeters. Dimensions are in meters.

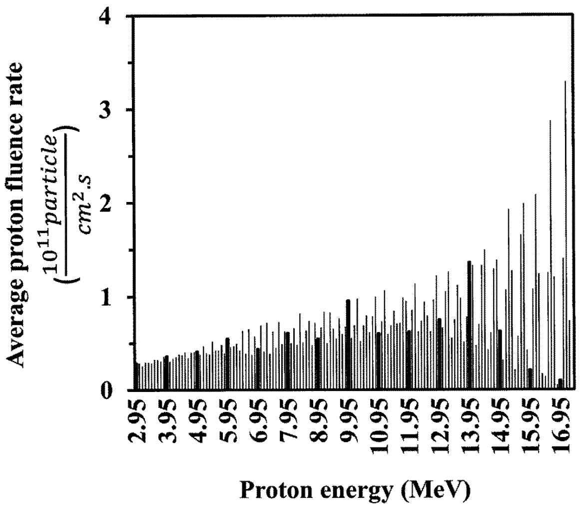

Fig. 2. Average proton fluence rate inside the enriched water target.

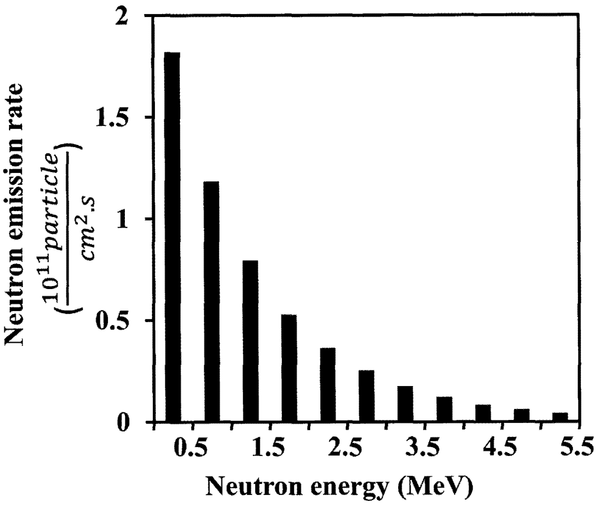

Fig. 3. The neutron spectra generated by proton bombardment of the liquid target.

Table 1. Average total neutron and proton fluence rate inside the liquid target room equipment

Equipment	Total neutron fluence rate (n/cm^2·s)	Total proton fluence rate (p/cm^2·s)
Spherical silver container of FDG target	2.44E+10	1.55246E+11
Conical steel container of Kr target	2.35E+07	3501.97
Titanium window (target side)	6.16E+10	8.81977E+12
Titanium window (vacuum side)	2.05E+10	8.81935E+12
Kr-81m target beam line	1.52E+07	424.2
Switching magnet	3.81E+06	1.47401
^{18}FDG target beam line	1.10E+08	64 763.5

1.06E+13 (p/cm^2.s). The average proton fluence rates inside the target were calculated for the energy range from 2.85 to 17.35 MeV by considering the energy bins equal to 0.1 MeV. The results are summarized in Fig. 2.

Bombardment for 1.5 h of the enriched $H_2{}^{18}O$ by a proton beam of energy 18 MeV and a proton current of 16 μA, yielded 22.2 GBq of ^{18}F measured at the end of bombardment. By considering the same conditions, using a MC simulation, Eqs. (1) and (2), results of Fig. 2 and ^{18}F production cross section [11], the radioactivity of ^{18}F calculated at the end of bombardment was 27.3 GBq. The relative errors in the MC calculations to obtain all fluence and dose rates were less than 0.05. Because the neutrons which exit from the target body penetrate inside the other equipment of the target room, nuclear reactions and radioactivation will occur in these components. For neutrons that exit from the target body, the total emission rate obtained through the MC method was 5.6E+11 (n/s) and its spectrum in the energy range of 0.5 to 15.5 MeV, by considering energy bin equal to 0.5 MeV was calculated and for the biggest fluences is shown in Fig. 3. As Figure 3 shows, the neutrons emission spectra indicate a most probable energy about 0.5 MeV and our calculations showed that the maximum energy of produced neutrons is up to 15.5 MeV.

In Table 1 the average total neutron and proton fluence rate inside the 6 pieces of the equipments mentioned above have been listed.

Using the MC method, average neutron and proton fluence rate spectra inside all walls of the target room and its maze were calculated. The results of this effort showed that only 6 surrounding walls of the target contributed to the whole body dose and other walls in the maze have no effect on the environment dose.

After MC calculation of proton and neutron fluence spectra for the 6 cases mentioned above, activities of the produced radioisotopes were determined by using Eqs. (1) and (2). The proper cross sections were obtained from the TENDL-2009 library [7], by the use of JANIS Nuclear Data Display Program (http://www.oecd-nea.org/janis/).

Results of this research showed that the cylindrical silver body of the enriched $H_2{}^{18}O$ target caused the main dose to the ICRU phantoms (more than 80% of total dose in phantoms was received from it). The most important nuclear reactions which occur in the silver target and produce radioactive materials and gamma photons have been summarized in Table 2.

The magnitude of the whole body dose depends on the three time-dependent factors:

a) Duration of the bombardment, depending on the desired activity of ^{18}FDG.
b) Time passed after the bombardment, it must be elapsed to allow the short-lived radioisotopes, produced in the target room equipment and its structures, to decay until the whole body dose became less than ICRP 60 limiting dose (25 μSv in an hour) [5].
c) Duration of repair depending on the kind of malfunction and the skill of the staff.

For various times of bombardment, the elapsed time which was needed to reduce the whole body dose of

Table 2. The most important nuclear reactions that occur in the silver target

Reaction	Half-life (h)	Q-value (MeV)
^{107}Ag (p,n) ^{107}Cd	6.5	1.417
^{109}Ag (p,n) ^{109}Cd	11 128.6	0.094
^{109}Ag (n,p) ^{109}Pd	322.32	1.1159

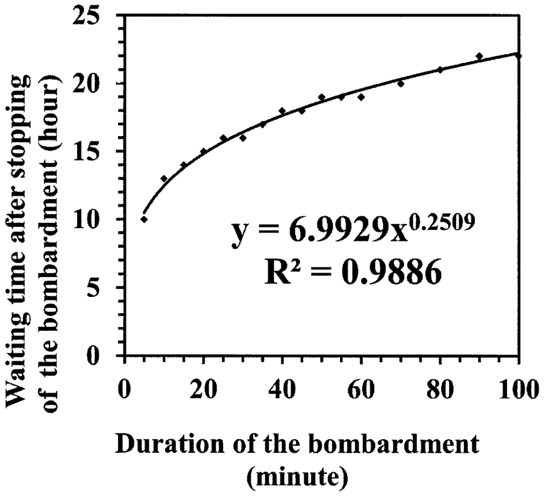

Fig. 4. Elapsed time after stopping of the bombardment to reach the ICRP criteria (25 μSv in an hour) vs. bombardment duration. The bombarded target remains in the target room (the correlation and its *R*-squared value have been shown).

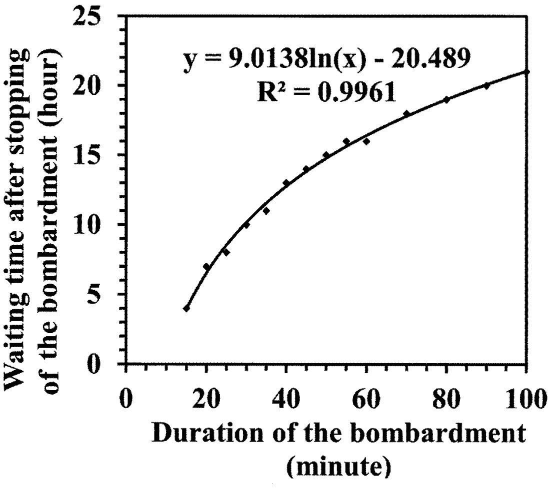

Fig. 5. Elapsed time after stopping of the bombardment to reach the ICRP criteria (25 μSv in an hour) vs. bombardment duration. The bombarded target has been removed from the target room (the correlation and its *R*-squared value have been shown).

each ICRU phantoms until it reached the ICRP 60 limit (25 μSv in an hour) were calculated. The results are shown in Figs. 4 and 5 for the bombarded target kept inside and outside of the target room, respectively.

The correlation between duration of bombardment and waiting time after the bombardment is shown in Figs. 4 and 5, wherein x is the duration of bombardment in minutes and y is the waiting time after the end of bombardment, necessary to reach the ICRP criteria.

Conclusion

The results of this research showed that the decision about doing or not doing the repair strongly depends on the radioactivity of the target and its environment. Target room radioactivity depends on the duration of the bombardment, target material, proton beam current and its energy. In order to repair interior parts of the target room, the personnel should wait more than 6 h for the decay of isotopes produced in the accelerator and facility structures, if the duration of bombardment was as short as 1 min. Within this period of time, the desired radioactivity of the target is lost. So, if it were possible, it would be better to remove the target from the beamline. The results showed that the repair can start immediately after stopping of the proton bombardment only if the target has been ejected from the target room and the duration of bombardment has not taken more than 10 min. Also the time sharing between the operators reduce the absorbed dose.

In normal conditions of ^{18}FDG production, the cyclotron should run continuously for about 90 min. Then, the target should be removed from the target room. In this situation the personnel must wait 20 h to meet the ICRP criteria before they obtain the permission to walk into the target room for preventative or corrective maintenance.

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