ORIGINAL PAPER

International Journal of Occupational Medicine and Environmental Health 2022;35(6):753–760
https://doi.org/10.13075/ijomeh.1896.01992

# EXPOSURE TO IONIZING RADIATION BY SERVICE PERSONNEL WORKING WITH CYCLOTRONS USED TO PRODUCE RADIOPHARMACEUTICALS IN PET DIAGNOSTICS

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**Abstract**
**Objectives:** While working with cyclotrons used for the production of radiopharmaceuticals, workers can experience significant exposure to the adverse effects of ionizing radiation. The aim of this paper was to determine the typical level of such exposure received by such personnel while servicing cyclotrons. **Material and Methods:** Exposure was assessed using TLD detectors placed in an anthropomorphic phantom, as well as dose meter to determine whole body and eye lens exposure. The phantom was placed in locations receiving the greatest exposure to ionizing radiation during service activities. The time spent by employees during servicing was assessed based on routine visits by service technicians. The obtained results were compared with readings of detectors worn by employees during service activities. **Results:** The highest equivalent doses in the thoracic area were found to be received by the lungs (211.16 μSv/year). In the head and neck area, the highest dose was measured in the eye lens (3410 μSv/year). The effective dose for the whole body was found to be 1154.4 μSv/year, based on the phantom, and 149 μSv per service visit (1192 μSv/year), based on the dose meters carried by the workers. **Conclusions:** Service workers are exposed to significant doses of ionizing radiation, representing a clear radiological protection issue. To reduce exposure to eye lenses, it is recommended to use protective goggles when working with highly-radioactive elements. Int J Occup Med Environ Health. 2022;35(6):753–60

**Key words:**
**nuclear medicine, PET, equivalent dose, service, radiological protection, cyclotron**

## INTRODUCTION

In medicine, the use of ionizing radiation results in exposure not only to patients and the personnel conducting the medical procedures, but also to the employees who service the equipment, perform periodic maintenance and correct failures. Many studies have examined the level of exposure to ionizing radiation received by medical personnel during treatments or examinations [1–3]. Unfor-

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Received: February 27, 2022. Accepted: June 23, 2022.
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tunately, very few have examined the personnel performing maintenance and repair of radiological equipment and are not directly related to the medical procedures themselves.

The aim of this study was to determine the exposure to ionizing radiation by personnel performing service activities on a cyclotron used to produce radiopharmaceuticals for PET diagnostics. Cyclotrons, due to their structure and the nature of their operation, represent considerable sources of exposure to ionizing radiation, both during operation and afterwards. During cyclotron operation, the personnel in the cyclotron control room are exposed to a mixture of neutrons and gamma radiation generated in nuclear reactions during isotope production [4–9]. In addition, due to the presence of radioisotopes formed in various parts of the cyclotron by nuclear activation by accelerated protons, gamma radiation continues to be emitted after the equipment is turned off [10–17] (Table 1). Due to the increasingly common use of PET diagnostics, and thus the growing number of cyclotrons used to produce radioactive isotopes, there is a growing need to determine the level of exposure to the personnel performing regular servicing activities on the equipment.

## MATERIAL AND METHODS

The cyclotron used in this work is the Eclipse HD (Siemens, Munich, Germany), which produces beam of 11 MeV protons, which is used to produce isotope $^{18}$F by bombarding water enriched with $^{18}$O. The degree of water enrichment is >95% and its chemical purity >99.9999%. In a typical production run [$^{18}$O] $H_2O$ is irradiated for 90 min, producing an average of 100 GBq $^{18}$F. Assuming about 200 production runs a year, the total activity is 20 TBq. The equipment can also be used to produce isotope $^{11}$C by irradiating an $N_2/O_2$ gas mixture with a proton beam. In this mixture, the maximum oxygen content is 2.5%. A typical production run lasts 50 min, resulting in 40 GBq of product. With about 200 production runs a year, this gives a total activity of 8 TBq [2].

However, due to interactions with the proton beam or high-energy secondary neutrons, many radioisotopes become trapped in cyclotron parts. Such activation processes are observed in:

- the beam path control elements situated near the exit of the cyclotron: graphite extraction films, beam deflectors, collimators;
- foils forming the entrance window of the target; this is made of Havar's alloy (Co [42%], Cr [19.5%], Ni [12.7%], W [2.7%], Mo [2.2 %], Mn [1.6%], C [0.2%], and Fe);
- copper mesh supporting foils, used to increase the window resistance to high pressures inside the target;
- silver target body.

Spectrometric measurements were performed around a cyclotron left to cool for 1 day using a portable scintillation spectrometer. The measured spectrum showed a wide spectrum of Compton radiation, with a maximum in the range of 100–125 kV. Such intense Compton scattering made it impossible to identify the isotopes in the obtained spectrum; however, these measurements provided a guide to the calibration energy range of the TLD detectors used in studies with the anthropomorphic phantom.

A CIRS anthropomorphic phantom was used to determine the exposure level of service workers [18]. This phantom simulates the build of an adult male with a height of 173 cm and weight of 73 kg. The phantom is divided into 2.5 cm layers with organ positions marked; TLD detectors can be placed inside the dummy to measure the doses received by particular organs. The present study used MCP-N TLD detectors (Radcard, Kraków, Poland) calibrated in units of Hp(10), corresponding to the energy spectrum emitted by the excited elements of the cyclotron. Two TLD detectors were placed in each appropriate hole in the dummy to calculate the equivalent

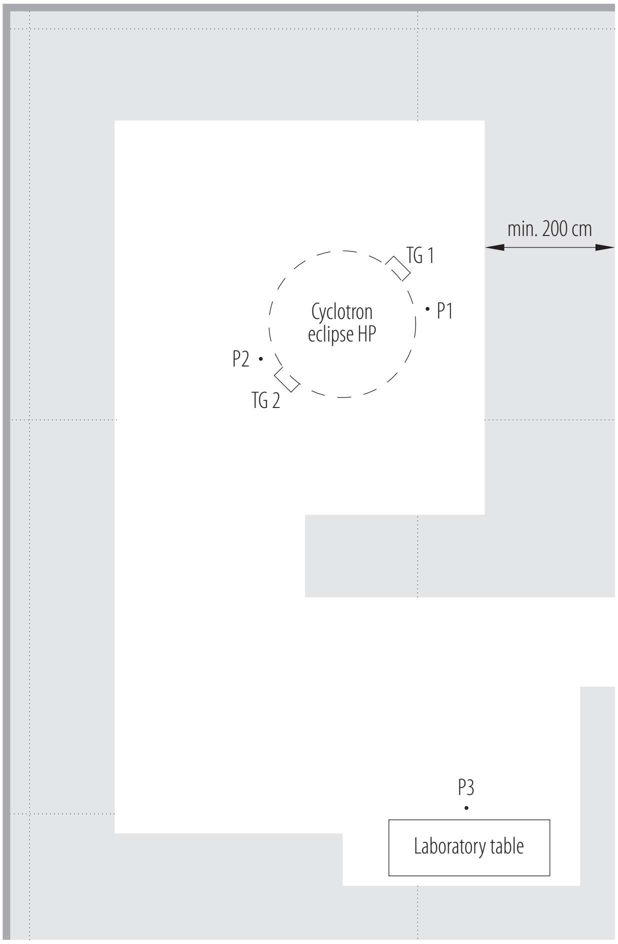
**Table 1.** Summary of reported radionuclides and methods for their identification during routine production of [${}^{18}$F]FDG based on literature from 2004–2021

| Reference | Accelerated particles/ target body and foil | Measured sample | Nuclide |
|---|---|---|---|
| Ferguson et al. [10] | 16.5 MeV protons/silver, Havar | FDG synthesis cassettes | ${}^{51}$Cr, ${}^{52,54}$Mn, ${}^{56,57,58}$Co, ${}^{95m,96}$Tc, ${}^{109}$Cd, ${}^{182,183}$Re |
| O'Donnell et al. [11] | 16 MeV protons/silver, Havar | Havar foil after 18 days cooling | ${}^{48}$V, ${}^{51}$Cr, ${}^{52,54}$Mn, ${}^{56,57,58}$Co, ${}^{182,183}$Re |
| Kambali et al. [12] | 11 MeV protons/silver, Havar | outer surface of the cyclotron chamber | ${}^{54}$Mn |
| | | inner and outer surface of the cyclotron shielding | ${}^{54}$Mn, ${}^{65}$Zn, ${}^{152}$Eu |
| | | Havar foil | ${}^{56}$Co |
| | | silver body | ${}^{110m}$Ag |
| | | rear screws | ${}^{52,54}$Mn, ${}^{60}$Co |
| Fujibuchi et al. [13] | 17 MeV protons, 10 MeV deuterons | hole to target box | ${}^{22}$Na, ${}^{60}$Co |
| | | deflector and magnatic channel | ${}^{54}$Mn, ${}^{60}$Co, ${}^{65}$Zn |
| Ito et al. [14] | 9.6 MeV protons/silver, Havar | irradiated water ([${}^{18}$O]$H_2$0/${}^{18}$F$^-$) | ${}^{52}$Mn,${}^{55}$Fe, ${}^{55,56,57,58}$Co, ${}^{59}$Ni, ${}^{95,96}$Tc, ${}^{109}$Cd |
| | | puridine, separation column | ${}^{52}$Mn, ${}^{55,56,57,58}$Co, ${}^{59}$Ni, ${}^{95,96}$Tc, ${}^{109}$Cd |
| | | recovered enriched water | ${}^{52}$Mn,${}^{55}$Fe, ${}^{55,56,57}$Co, ${}^{59}$Ni, ${}^{109}$Cd |
| | | the other componens | ${}^{52}$Mn, ${}^{55,56,57}$Co, ${}^{95,96}$Tc, ${}^{109}$Cd |
| Marengo et al. [15] | 16.5 MeV protons/silver, Havar | terget filters | ${}^{48}$V, ${}^{51}$Cr, ${}^{52,54}$Mn, ${}^{56,57,58,60}$Co, ${}^{57}$Ni, ${}^{95m,96}$Tc, ${}^{105,106m}$Ag, ${}^{109}$Cd, ${}^{183}$Re |
| | | purification water column | ${}^{48}$V, ${}^{51}$Cr,${}^{52,54,56}$Mn, ${}^{55,56,57,58}$Co, ${}^{57}$Ni, ${}^{95,95m,96,98}$Tc, ${}^{105,106m}$Ag, ${}^{109}$Cd, ${}^{181,182,182m,183,184,186}$Re |
| | | recovered water | ${}^{51}$Cr, ${}^{52,54}$Mn, ${}^{55,56,57,58,60}$Co, ${}^{57}$Ni, ${}^{95,95m,96}$Tc, ${}^{109}$Cd, ${}^{182m,183,186}$Re |
| | | purification FDG column | ${}^{51}$Cr, ${}^{52,54,56}$Mn, ${}^{55,56,57,58}$Co, ${}^{57}$Ni, ${}^{95,95m,96}$Tc, ${}^{109}$Cd, ${}^{181,182, 183,184,186}$Re |
| Dlugosz-Lisiecka et al. [16,17] | 11 MeV protons/silver, Havar | separation column and purification column | ${}^{107}$Cd, ${}^{109}$Cd |
| | | Havar foil | ${}^{56}$Co, ${}^{57}$Co, ${}^{60}$Co, ${}^{54}$Mn |

dose to individual organs. Additionally, an individual dosimeter with TLD detectors was placed on the anthropomorphic phantom, at the level of the heart, to assess personal dose equivalent, Hp(10).

The full annual service scope of the cyclotron includes 6-week, quarterly, semi-annual and annual tests. During the 2 service visits preceding the measurements, the average stay of service employees in specific places of the cyclotron bunker was measured; the results indicate that the mean total exposure time for service personnel is around 2.5 h, comprising about 2 h and 10 min at the cyclotron, and 20 min at the laboratory table. It was found that workers spend an equal amount of time at both targets of the cyclotron.

Measurements were performed using the anthropomorphic phantom placed at the measurement points marked in Figure 1 (P1, P2, P3); the measurement times were determined based on the previous observations of the service personnel. In addition, to model 4 service visits, the phantom was placed at the cyclotron 4 times, 2 times



P – point; TG – target.

**Figure 1.** Arrangement of measurement points in the cyclotron bunker

for each target, where the service staff carry out activities directly at the cyclotron.

The door securing the entrance to the cyclotron bunker can be opened if the radiation dose rate inside the bunker is <10 mSv/h (10 000 μSv/h). On average, it took 7 h from the end of production for the dose rate to drop to this level. Planned service work usually starts at the beginning of the week, i.e., after about 72 h from the end of the last production run. The dose rate remained constant during the 2.5-hour measurement period, performed a relatively long time from the end of production. However, throughout the year, service works are performed; these begin when the dose rate in the cyclotron bunker drops below the value allowing safe entry.

In addition, if there is no need to work directly at the cyclotron, employees can perform service activities on radioactive materials at a laboratory table separated by 12 cm thick lead bricks. To assess the exposure during such activities, the phantom was placed at the laboratory table in the bunker for 20 min during the final service visits; during this time, highly-active elements of the cyclotron were left on the table. The dose rate in the work environment was measured using a Thermo Scientific FH 40G-10 radiometer (Thermo Fisher Scientific, Waltham, USA) calibrated in the Secondary Standards Laboratory using $^{137}$Cs and $^{60}$Co sources.

The maintenance procedures performed during service procedures: vacuum system (mechanical and diffusion pumps), water system, extraction system, target system and all the others.

Each service activity involves exposure to ionizing radiation. Especially works related to cleaning targets, reconstruction of the extraction, regeneration and cleaning system of the ion source carry a very high exposure to gamma radiation.

The uncertainty in measuring the dose levels in individual organs determined with the anthropomorphic phantom is a standard uncertainty. In the case of measurements with the FH 40G-10 radiometer, the measurement uncertainty is the expanded uncertainty, defined as the standard uncertainty of the measurement and incurred by the coverage factor k = 2.

## RESULTS

Equivalent doses were calculated for individual organs, according to the time and location of employees during service activities performed in 1 centre for 1 year (Table 2). Doses were measured at 2 cyclotron production channels: $F_1$ and $F_2$. Channel $F_1$ contains targets to produce $^{18}$F and $^{11}$C, while channel $F_2$ is used for only $^{18}$F

**Table 2.** Equivalent doses calculated based on measurements in the anthropomorphic phantom in PET centre in 2021

| Organ | Dose equivalent [µSv/year] (V (SE)) | | |
|---|---|---|---|
| | canal | | total |
| | $F_1$ | $F_2$ | |
| Brain | 24.74 (7.91) | 9.07 (2.60) | 17.87 (7.85) |
| Eyes | 41.89 (9.59) | 14.77 (3.20) | 30.44 (9.71) |
| Thyroid | 141.88 (24.23) | 65.36 (6.19) | 111.09 (21.72) |
| Spinal cord | 13.76 (9.91) | 8.35 (2.53) | 11.60 (9.06) |
| Thymus | 35.62 (4.61) | 20.18 (2.79) | 29.45 (5.58) |
| Heart | 251.99 (41.17) | 143.16 (9.79) | 208.46 (36.92) |
| Lungs | 253.54 (120.40) | 147.58 (50.78) | 211.16 (123.83) |
| Liver | 75.85 (23.08) | 43.77 (10.79) | 63.02 (24.68) |
| Pancreas | 149.47 (52.68) | 95.12 (23.10) | 127.73 (54.66) |
| Stomach | 174.43 (60.04) | 106.37 (26.77) | 147.21 (62.77) |
| Kidneys | 115.73 (29.66) | 80.55 (22.89) | 101.78 (38.87) |
| Prostate | 110.37 (17.80) | 92.35 (11.51) | 103.16 (21.03) |
| Bladder | 48.09 (9.49) | 34.97 (5.98) | 42.96 (11.19) |
| Bowels | 207.64 (36.36) | 125.38 (13.16) | 174.74 (35.67) |
| Testicles | 109.46 (12.59) | 97.43 (7.56) | 104.65 (14.52) |

SE – standard error; V – value.

production. The equivalent doses for individual organs were calculated using a weighting factor ($W_T$), in accordance with the ICRP 103 report [19]. To assess the radiation level of the elements removed from the cyclotron, the radiation dose rate was measured at the laboratory table (Table 3). Measurements were made at 5 cm and at 50 cm from the surface of radioactive elements, and behind a 12 cm thick shield of lead bricks.

## DISCUSSION

The dose distribution around the activated cyclotron is not uniform [6,20]. The greatest exposure is observed at the point in the lumen of the canal, close to the cyclotron targets. The cyclotron used in the present work has 2 channels, marked as $F_1$ and $F_2$, both of which require regular servicing. $F_1$ is used to produce both $^{18}F$ and $^{11}C$, and so has a higher dose rate than $F_2$ (Table 2). Service workers usually try not to stay in the channel lumen for long periods, but longer visits are sometimes necessary.

During service visits, activities are performed on both channels. Table 2 presents the equivalent doses received by individual organs in an employee performing service activities throughout the year. When analysing these doses, it is important to note the level of cardiac (208.46 µSv/year) and lung exposure (211.16 µSv/year); these values are higher by a factor of 2.55 than the mean values noted in other organs. These values are most strongly affected by activities performed at the cyclotron as the heart and lungs are at the same level of the targets placed in the canals when the worker stands there:

**Table 3.** Exposure for activities performed at the laboratory table

| Radioactive element | Dose [μSv/h] (V (U)) | | |
|---|---|---|---|
| | distance | | behind lead bricks |
| | 5 cm | 50 cm | |
| Copper target mesh | 14 309.10 (2432.55) | 292.50 (49.73) | 1.94 (0.33) |
| The silver body of the target | 193.05 (32.82) | 3.80 (0.65) | 0.19 (0.03) |
| Havar foil | 3393.00 (576.81) | 67.86 (11.54) | 1.52 (0.26) |

U – expanded uncertainty; V – value.

the radiation from the collimated beam leaves the lumen of the canal, irradiating the organs closest to it.

Work at the laboratory table is performed with the use of a 12 cm lead sheath and various grippers, in the case of the most radioactive elements (Table 3). During such work, the organs in the thoracic and pelvic areas receive a lower dose due to the protection used and the relatively short duration of the activity, i.e., approx. 10% of the total exposure time. The lowest equivalent dose was measured in the spinal cord (11.6 μSv/year). All activities on the cyclotron are performed without the use of additional radiation shields, i.e., lead walls or protective aprons.

When analyzing the doses to which the service worker is exposed, special attention should be paid to the elements that are disassembled from the cyclotron, as these elements directly interact with the accelerated proton beam, and the nuclear reactions take place in their structure [10]. The most radioactive components that are removed during service work include the copper target mesh, the silver target body and the Havar foil (Table 3); of these, the most radioactive are the copper target mesh and Havar foil. It is worth noting, however, that the radiation dose rate from these elements very rapidly decreases with distance: it decreases fifty times at 50 cm.

With their radiation levels being so high, all work on the components must be performed behind a lead shield, using appropriate grippers. Even so, despite the use of grippers and covers, these elements pose a significant radiological threat to service employees, especially since they must be replaced at each service visit. Although these elements can also be sources of surface contamination when damaged during service work, no surface contamination was found in the present study.

Regarding whole body exposure, measured on the phantom, it can be concluded that, assuming a 2.5-hour exposure, an employee receives 144.3 μSv during each service visit. Based on 8 visits/year in a single centre, this would indicate an annual exposure of 1154.4 μSv. It should be noted that this measurement includes both the service work performed at the cyclotron and at the laboratory table. To confirm the dose value for the whole body measured on the phantom during service visits, employees were equipped with individual electronic dosimeters, which made it possible to read the dose quickly. The mean value of the dose indicated by the electronic dosimeter during 5 service visits was 149 μSv, which confirms the results obtained from phantom measurements.

When assessing exposure, particular attention should be paid to exposure of the eye lenses. The European Council Directive 2013/59 / EUROATOM [21] and the legal regulations in force in Poland introduce an acceptable dose limit for eye lenses of 20 mSv/year (20 000 μSv/year). The introduction of a dose limit for eye lenses necessitates the need to monitor such exposure in workers performing activities involving exposure to ionizing radiation [2]. The present measurements indicate the dose in the eye lenses to be approx. 3.41 mSv/year (3410 μSv/year) in maintenance workers, which is 17% of the permissible annual dose limit established by applicable law. Note that the eye lenses are strongly exposed to ionizing radiation during all servicing activities, and that work on the cyclotron or on the laboratory bench is performed without the use of any eye protection.

The obtained annual service worker exposure of 1154.4 μSv applies to work performed on only 1 site using a Siemens cyclotron. As 4 such cyclotrons are installed in Poland, it can be assumed that service personnel can potentially receive a dose of 4.6 mSv/year (4600 μSv) by performing scheduled service activities. This dose represents category B occupational exposure. However, it should be remembered that this value only applies to planned visits and does not include equipment failures and other unpredictable events, and the true value may exceed the operational limit of 6 mSv/year (6000 μSv), i.e., putting the worker in category A of exposure to ionizing radiation.

This analysis demonstrates the importance of workers being equipped with individual ionizing radiation dose meters, rather than estimating exposure risk based on environmental dosimetry, as is the case in every facility using cyclotrons to produce radiopharmaceuticals. The distribution of radiation in the cyclotron bunker is very heterogeneous, and hence detectors placed in well-defined places, usually at the entrance door, are not suitable for accurate dose estimations in rooms with potentially high radiation levels. An environmental radiation level monitoring system is an excellent tool for general monitoring of the working environment but over-generalizes the individual exposure level of workers carrying out certain activities.

## CONCLUSIONS

It is important to determine the doses of ionizing radiation received by service workers to ensure occupational safety. It is imperative that these individuals wear meters measuring eye lens dose, hand dose and whole body dose. Protective goggles should be used to reduce the dose in the lenses. Service activities should always be carried out in accordance with strictly defined work safety procedures ensuring minimal contact with the radioactive elements of the cyclotron and thus reducing exposure. To further minimize exposure to ionizing radiation, service personnel should have extensive knowledge on radiation protection and keep it up to date by participation in regular radiation protection training.

## REFERENCES

1. Krajewska G, Pachocki KA, Assessment of exposure of workers to ionizing radiation from radioiodine and technetium in nuclear medicine departmental facilities. Med Pr. 2013;64(5): 625-630. https://doi.org/10.13075/mp.5893.2013.0061.
2. Domienik-Andrzejewska J, Kałużny P, Piernik G, Jurewicz J, Occupational exposure to ionizing radiation and lens opacity in interventional cardiologists. Int J Occup Med Environ Health. 2019;32(5):663-675. https://doi.org/10.13075/ijomeh.1896.01456.
3. Wrzesień M, Albiniak Ł, Biegała M, The structure of Hp(0.07) values obtained by the nuclear medicine personnel during 18F-FDG production and injection. Radiat. Prot. Dosim. 2019;184 (2), 224–229. https://doi.org/10.1093/rpd/ncy203.
4. Cyclotron produced radionuclides: operation and maintenance gas and liquid targets. — Vienna: International Atomic Energy Agency, 2012.
5. Radiation protection in newer medical imaging techniques: PET/CT. — Vienna: International Atomic Energy Agency, 2008.
6. Biegała M, Jakubowska T, Levels of exposure to ionizing radiation among the personnel engaged in cyclotron operation and the personnel engaged in the production of radiopharmaceuticals, based on radiation monitoring system. Radiation Protection Dosimetry, 2020; 189 (1), 56–62 https://doi.org/10.1093/rpd/ncaa012.

7. Jakubowska T, Długosz-Lisiecka M, Estimation of effective dose using two ICRP criteria, applied to radiation protection of personnel in an unshielded PET cyclotron facility. Radiat. Phys. Chem. 2020;171(108688), https://doi.org/10.1016/j.radphyschem.2020.108688.
8. Cruzate JA. Estimate of the radiation source term for $^{18}F$ production via thick $H_2^{18}O$ targets bombarded with 18MeV protons. Radiat. Phys. Chem. 2015; 117: 54-58, https://doi.org/10.1016/j.radphyschem.2015.07.018.
9. Alloni D, Prata M, Characterisation of the secondary neutron field generated by a compact PET cyclotron with MCNP6 and experimental measurements. Appl. Radiat. Isot., 2017, 128, 204-209, https://doi.org/10.1016/j.apradiso.2017.07.031.
10. Ferguson D, Orr P, Gillanders J, Corrigan G, Marshall C. Measurement of long lived radioactive impurities retained in the disposable cassettes on the Tracerlab MX system during the production of [$^{18}F$] FDG. Appl Radiat Isot. 2011;69(10): 1479-85. https://doi.org/10.1016/j.apradiso.2011.05.028.
11. O'Donnell RG, Leon Vintro L, Duffy GJ, Mitchell PI. Measurement of the residual radioactivity induced in the front foil of a target assembly in a modern medical cyclotron. Appl Radiat Isot. 2004;60:539–542. https://doi.org/10.1016/j.apradiso.2003.11.073.
12. Kambali I, Suryanto H, Parwanto. Radioactive by-products of a self-shielded cyclotron and the liquid target system for F-18 routine production. Australas Phys Eng Sci Med. 2016;39, 403–412. https://doi.org/10.1007/s13246-016-0426-1.
13. Fujibuchi T, Toyoda T, Baba S, Umezu Y, Komiya I, Sasaki M, et al. Evaluation of the distribution of activation inside a compact medical cyclotron. Appl Radiat Isot. 2017; 124, 27-31. https://doi.org/10.1016/j.apradiso.2017.02.045.
14. Ito S, Saze T, Sakane H, Nishizawa K. Analysis of radioactive byproducts in [18O] H2O used to produce 18F for [18F] FDG synthesis. Appl Radiat Isot. 2006; 64, 298–305 https://doi.org/10.1016/j.apradiso.2005.10.001.
15. Marengo M, Lodi F, Magi S, Cicoria G, Pancaldi D, Boschi S. Assessment of radionuclid icimpurities in2-[18F]fluoro-2-deoxy-d-glucose ([18F]FDG) routine production. Appl. Radiat. Isot. 2008; 66, 295–302. https://doi.org/10.1016/j.apradiso.2007.08.015.
16. Dlugosz-Lisiecka M, Jakubowska T, Zbrojewska M. Formation of Cd-107 radionuclide impurities during F-18 production. Appl. Radiat. Isot. 2019; 147,48-53. https://doi.org/10.1016/j.apradiso.2019.02.007.
17. Długosz-Lisiecka M, Jakubowska T, Zawada A. High-Level Radioactive Wastes from 18F and 11C Isotopes Production; J. Hazard. Toxic Radioact. Waste. 2021; 25(2),04020072, https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000580.
18. Santos JS, Uusi-Simola J, Kaasalainen T, Aho P, Venermo M. Radiation doses to staff in a hybrid operating room: an anthropomorphic phantom study with active electronic dosimeters. Eur J Vasc Endovasc Surg. 2020; 59, 654-660. https://doi.org/10.1016/j.ejvs.2020.01.018.
19. ICRP, 2007. Recommendations of the International Commission on Radiological Protection, vol. 103 ICRP Publication.
20. Stępińska A, Jakubowska T, Biegała M, Rosner M. Pomiar promieniowania jonizującego pochodzącego od komponentów tarcz cyklotronu stosowanego do produkcji radioizotopów wykorzystywanych w diagnostyce PET. Inżynier i Fizyk Medyczny. 2018;7(6):366–367. Polish.
21. European Council Directive 2013/59/Euratom on basic safety standards for protection against the dangers arising from exposure to ionising radiation and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. OJ of the EU. L13; 57: 1–73 (2014).

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