

# 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

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**This paper aims to determine the levels of exposure to neutron and photon radiation among the personnel engaged in cyclotron operation and the personnel engaged in the production of radiopharmaceuticals, with the use of the environmental radiation monitoring system (RMS) installed in the positron emission tomography laboratory. The annual exposures of employees operating the cyclotron measured with the use of the RMS system are:  $1.39 \pm 0.16$  mSv in case of photon radiation and  $2.61 \pm 0.14$  mSv in case of neutron radiation. In the case of employees in the radiopharmaceuticals' production zone, the annual exposures measured by means of the RMS system are  $0.15 \pm 0.03$  mSv in case of photon radiation and  $0.11 \pm 0.01$  mSv in case of neutron radiation. The exposure levels among the personnel engaged in cyclotron operation and the personnel engaged in the production of radiopharmaceuticals are below the permissible radiation dose limits.**

## INTRODUCTION

Nuclear medicine is a field of medicine in which personnel receive high doses of ionizing radiation<sup>(1)</sup>. This probability is particularly high in laboratories in which radioactive isotopes are produced for the purpose of diagnostics using positron emission tomography (PET). These facilities are equipped with circular accelerators in which short-lived radioactive isotopes used for the production of radiopharmaceuticals are produced by nuclear reactions<sup>(2–4)</sup>. The highest radiation hazard in such a facility, apart from the radioactive isotope itself<sup>(5–7)</sup>, is a cyclotron being a source of neutron and photon radiation as well as a place of production of many other long-lived isotopes (not used in diagnostics) being a by-product of the production of a proper isotope<sup>(8,9)</sup>. The level of exposure depends on the shields used and the geometric layout of the cyclotron in the bunker as well as on the energy of the accelerated particles<sup>(10–15)</sup>.

This paper aims to determine the levels of exposure of cyclotron personnel and radiopharmaceutical production personnel to neutron and photon radiation, using the environmental radiation monitor system (RMS) installed in the PET laboratory.

## MATERIAL AND METHODS

The production of isotopes in the PET laboratory takes place with the use of the Siemens Eclipse HP cyclotron, which accelerates negative ions to the energy of 11 MeV. The total, maximum current of one cyclotron beam is 60  $\mu$ A. The cyclotron produces two radioisotopes for the needs of the laboratory, i.e. <sup>18</sup>F by the reaction of <sup>18</sup>O(p, n) <sup>18</sup>F and <sup>11</sup>C by the reaction of <sup>14</sup>N(p,  $\alpha$ ) <sup>11</sup>C<sup>(16,17)</sup>. The exposure assessment takes into account the doses generated during the production of <sup>18</sup>F and <sup>11</sup>C. The cyclotron is unshielded; therefore, the walls of the bunker are the basic shields against radiation. The cyclotron can supply two ion beams (TG1 and TG2), at the end of which there are carousels with targets containing the following respectively: for the production of <sup>18</sup>F, water enriched with <sup>18</sup>O, and for the production of <sup>11</sup>C, a gas mixture containing the <sup>14</sup>N isotope. Fluorine-18 is produced in targets positioned at the beam output at the TG1 and TG2 positions and carbon—11 only at TG1. The arrangement of the cyclotron in the bunker with the position of the beam outputs (TG1 and TG2) is shown in Figure 1. The measurement of doses was carried out using the RMS system, which consists of measuring probes

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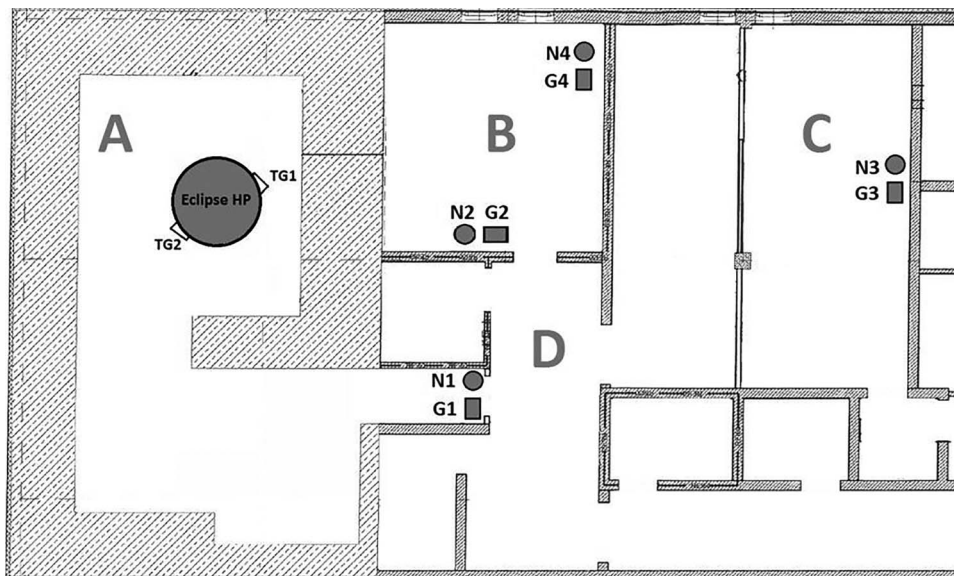


Figure 1. diagram of distribution of measuring points (A—cyclotron bunker, B—cyclotron control room, C—radiopharmaceutical production room, D—cyclotron zone corridor, N—neutron detectors, G—gamma detectors) and the location of the Eclipse HP cyclotron in the bunker along with the position of the beam outputs (TG1 and TG2).

distributed throughout the laboratory. In this paper, readings from detectors placed in the production zone were analyzed, the distribution of which is shown in Figure 1.

The RMS system consists of two types of detectors:

- Gamma radiation detector (Geiger–Müller detector), which measures the dose rate of a gamma radiation dose with energy from 0.08 to 1.5 MeV, in the range from  $10^{-7}$  to  $10^{-1}$  Sv per h;
- Neutron radiation detector (proportional cylindrical detector, filled with  $^3\text{He}$ , placed in a polyethylene ball with a diameter of 250 mm), measuring spatial neutron equivalent with energy from 0.025 to 16 MeV, in the range from  $10^{-7}$  to  $10^{-1}$  Sv per h.

Due to the fact that the workplace of the cyclotron operator in the control room is far from the RMS system detectors, additional measurements were made using the FH 40 G-10 meter with the neutron probe at the operator's worksite (N4 G4 measuring points).

The FH 40 G-10 meter consists of two types of detectors:

- Gamma radiation detector with a built-in proportional counter, performing a measurement of the spatial gamma radiation dose with an energy range from 30 keV to 4.4 MeV, measuring between  $10^{-9}$  and 1 Sv per h;

- Neutron radiation detector with  $\text{BF}_3$  moderator, which measures the dose rate of the neutron radiation dose with energy in the range of  $2.5 \times 10^{-5}$  keV–410 MeV, measuring the range from 0.1 nSv per h to 0.4 Sv per h.

## RESULTS

To estimate the amount of annual exposure to photon and neutron radiation among the production zone personnel (cyclotron operation and radiopharmaceutical production), the radiation dose rates were measured at points marked in Figure 1 for five production cycles of each isotope using appropriate beam outputs. The average dose performance results were multiplied by the time of radiopharmaceutical production and the number of production cycles of each radiopharmaceutical for individual beam outputs. Production takes place every working day, except on days when there is a maintenance inspection or equipment failures. Table 1 shows the average dose rates measured at measuring points in the production area.

During 12 months, 214 production cycles of radiopharmaceuticals took place, including the following:

- 78 production cycles of  $^{18}\text{F}$  at the FG1 target position;
- 68 production cycles of  $^{18}\text{F}$  at the FG2 target position;

**Table 1. Average dose rates obtained at individual measuring points.**

Channel— <sup>18</sup> F Detectors	TG1— <sup>18</sup> F Average dose ± SD [μSv per h]	TG2— <sup>18</sup> F Average dose ± SD [μSv per h]	TG1— <sup>11</sup> C Average dose ± SD [μSv per h]
G1	25.98 ± 2.85	66.13 ± 4.34	7.48 ± 1.75
N1	54.59 ± 3.84	236.56 ± 8.48	15.29 ± 3.18
G2	1.77 ± 0.28	4.71 ± 0.61	0.65 ± 0.15
N2	1.16 ± 0.09	5.27 ± 0.21	0.31 ± 0.07
G3	0.40 ± 0.08	0.67 ± 0.13	0.23 ± 0.06
N3	0.14 ± 0.02	0.71 ± 0.04	0.04 ± 0.02
G4	0.31 ± 0.06	0.68 ± 0.09	0.16 ± 0.03
N4	0.80 ± 0.12	2.76 ± 0.33	0.20 ± 0.05

**Table 2. Annual radiation doses calculated at appropriate measurement points.**

Type of dosimeter	Dose per year [mSv]	Total dose per year [mSv] (G + N)	Factor <i>k</i> (N/G)
G1	11.86 ± 0.99	48.70 ± 0.44	3.11 ± 0.03
N1	36.84 ± 1.69		
G2	0.84 ± 0.02	1.65 ± 0.02	0.97 ± 0.01
N2	0.81 ± 0.03		
G3	0.15 ± 0.03	0.25 ± 0.01	0.74 ± 0.02
N3	0.11 ± 0.01		
G4	0.12 ± 0.01	0.54 ± 0.02	3.34 ± 0.05
N4	0.41 ± 0.06		

- 68 production cycles of <sup>11</sup>C at the FG1 target position.

The average production time determined on the basis of the measurements made was as follows:

- 99.6 ± 6.3 min—for the production of the <sup>18</sup>F at the FG1 target position;
- 108.2 ± 11.1 min—for the production of the <sup>18</sup>F at the FG2 target position;
- 43.4 ± 1.52 min—for the production of the <sup>11</sup>C at the FG1 target position.

In all measurements, the background radiation was taken into account, which was determined during a period of 60 min before starting the production. For gamma radiation, it was 0.171 ± 0.050 μSv per h, while for neutron radiation it was 7.0 ± 0.1 nSv per h.

Based on the data from Table 1, as well as the exposure time and the number of exposures, the annual dose was calculated at various measurement points. Data are presented in Table 2.

For the estimation of the dose for the personnel operating the cyclotron, it was assumed that during the operation of the device, they spend on average 95% of the time in the control room and a maximum of 5% of the time in the corridor. The dose for employees of the cyclotron zone was determined in two ways. In the first method, the dose was calculated based solely on the RMS system. The second method

used the RMS system and took into account the measurement taken directly besides the cyclotron control computer (G4, N4 points). Table 3 shows the calculated annual doses of photon and neutron radiation received by the employees operating the cyclotron and the working at the production of radiopharmaceuticals.

## DISCUSSION

When analyzing the distribution of doses around the cyclotron used in the production of isotopes for the PET diagnostics, it should be remembered that this device is also a source of neutron radiation generated by the reaction (p, n) both in the shield material itself and in the cyclotron elements located directly in the beam's area. In addition, the resulting neutrons may have sufficient energies to induce subsequent nuclear reactions and further, already neutron activation of the accelerator's elements. The presence of radioactive isotopes activated by protons and neutrons in the cyclotron elements locally increases the level of radiation around the device, even when it is switched off. The produced radionuclides include also those with long half-lives, for example: <sup>109</sup>Cd ( $T_{1/2} = 462$  d), <sup>54</sup>Mn ( $T_{1/2} = 312$  d). In the result, the increased radiation level is maintained over a period of several years<sup>(18)</sup>. However, it should be remembered that

**Table 3. Radiation doses in the cyclotron operating zone and in the radiopharmaceutical production room.**

Type of dosimeter	Measuring points	Dose per year [mSv]		Total dose per year [mSv] (G + N)	Factor $k$ (N/G)
		Gamma (G)	Neutrons (N)		
RMS	G1, N1 + G2, N2	1.39 ± 0.16	2.61 ± 0.14	4.00 ± 0.06	1.88 ± 0.03
RMS + FH 40 G-10	G1, N1 + G4, N4	0.71 ± 0.04	2.24 ± 0.11	2.95 ± 0.02	3.14 ± 0.02
RMS	G3, N3	0.15 ± 0.03	0.11 ± 0.01	0.26 ± 0.01	0.74 ± 0.01

the cyclotron's operators enter the bunker only in emergency situations, because the cyclotron is checked before its activation by means of cameras. After turning off the cyclotron, the RMS detectors located outside of the bunker indicate radiation at the level of the background. Therefore, exposure to radiation emitted by the cyclotron when it is turned off outside its bunker can be omitted.

The employee exposure analysis used the RMS probes located in the places where the cyclotron personnel are present during cyclotron operation and in which they are exposed to photon and neutron radiation generated by the accelerator.

When analyzing the average dose rates obtained at individual measurement points (Table 1), it can be seen that the highest dose rate is recorded by detectors located in the corridor leading to the bunker door. Particularly high dose rate is recorded during the production of  $^{18}\text{F}$  through the TG2 channel. This is due to the geometric arrangement of the channel relative to the detectors in Figure 2. In the case of production with the TG2 channel, the primary beam hits the shield located closer to the entrance door to the bunker and corridor. The detectors in this case also register a higher dose than the scattered radiation.

The situation changes in the case of production of  $^{18}\text{F}$  with the TG1 channel. In this case, the dose rate recorded in the corridor is 2.5 times lower for gamma radiation and 4.3 times lower for neutron radiation compared with the production through the TG2 channel. The TG1 channel is geometrically located further away from the corridor and from the bunker door. The resulting radiation is emitted directly to the outer wall of the bunker; hence, smaller dose rates inside the laboratory are registered.

In the case of production of  $^{11}\text{C}$  with the TG1 channel, the dose rate from gamma radiation is 3.5 times lower than in the case of production of  $^{18}\text{F}$  with this channel and 8.8 times lower than in the case of production of  $^{18}\text{F}$  with the TG2 channel. Similarly, for neutron radiation, the radiation dose rate decreases 3.6 times in the case of production of  $^{18}\text{F}$  with TG1 channel and 15.5 times in the case of  $^{18}\text{F}$  production with the TG2 channel. It should be kept in mind that as a result of a nuclear reaction whose final

product is  $^{11}\text{C}$ , neutrons do not only generate alpha particles and photon radiation. Neutron radiation in this case comes from the interaction of high-energy gamma and protons with elements of cyclotron and environment<sup>(19,20)</sup>.

When analyzing Table 1, it is worth noting the readings of G2, N2 detectors located on the wall at the entrance to the control room and the readings of G4, N4 detectors located on the cyclotron control panel in the control room. These two sets of detectors monitor the dose rate in the cyclotron control room, i.e. in the room in which the cyclotron personnel reside during the operation of the device. It is worth noting that the reading at the cyclotron operating panel is significantly lower compared to the reading of detectors located on the wall at the entrance to the control room regardless of the channel and the isotope that is being produced. The highest decrease in dose rate is observed for gamma radiation during the production of  $^{18}\text{F}$  through TG2 channel, i.e. 6.9 times, and the smallest when producing  $^{11}\text{C}$  by TG1 channel, i.e. 4 times. In the case of neutron radiation, the decrease in radiation is smaller and amounts to 1.5 times for the production of  $^{11}\text{C}$  and  $^{18}\text{F}$  by the TG1 channel and 1.9 times for the production of  $^{18}\text{F}$  by the TG2 channel. Such distribution of dose rates in the control room is very advantageous, because most of the time the operator is at the control desk, only a small fraction of the time it moves around the control room.

The dose rates measured in the area of radiopharmaceutical production are the highest in the case of the  $^{18}\text{F}$  production through the TG2 channel. They are, for gamma radiation, 1.7 times higher compared with the  $^{18}\text{F}$  production through TG1 channel and 2.9 times higher compared with the  $^{11}\text{C}$  production through the TG1 channel. In the case of neutron radiation, it is 5.1 times higher compared with the  $^{18}\text{F}$  production through the TG1 channel and 17.8 times higher compared with the  $^{11}\text{C}$  production through the TG1 channel. The increase in the dose rate during production with the TG2 channel is related to the arrangement of the channel output in the bunker and the geometry of the channels relative to the measuring detectors, similarly as in case of the G1, N1 detectors. There is also a decrease in the number of neutrons during the production of  $^{11}\text{C}$ .

Table 2 shows the annual doses calculated at measurement points, taking into account the number of production cycles and their time. It is worth noting that at points G1, N1 and G4, N4 there is a high ratio of the dose from neutron radiation to the dose derived from photon radiation. This indicates higher exposure to neutron radiation at these measurement points. At the remaining measurement points—G2, N2 and G3, N3—the exposure to neutron radiation is at a similar level or slightly lower than in the case of gamma radiation.

On the basis of the obtained data, the annual dose (Table 3) for the employees operating the cyclotron and the dealing with the production of radiopharmaceuticals was calculated at individual measurement points. It can be seen here in the first place how important the location of measurement points (probes of the environmental monitoring system) is. For the cyclotron operating personnel, taking the readings directly from the cyclotron control panel (the actual location of the operator) when calculating their annual total exposure to ionizing radiation results in 26% decrease in exposure compared with the reading obtained only from the RMS system. The RMS system for these employees overstates the radiation dose they receive on a yearly basis. However, from the point of view of radiological protection, getting an overestimated reading is safer than underestimating the dose.

When analyzing the components contributing to the total annual dose that the personnel receive, it can be seen that in the case of measurements performed only with the use of the RMS, the proportion of gamma radiation dose is 95% higher than in the case of dose estimation with the control panel measurement. It follows that the place where the control panel is located is better protected against gamma radiation compared with the installation site of the RMS system. The situation is different in the case of neutron radiation. Only 14% fewer neutrons are registered at the control desk compared to the RMS. This means that exposure to neutron radiation is uniform in the control room.

When analyzing Table 3, it is also worth noting that regardless of the measurement method, a high neutron radiation dose is observed as compared to the gamma radiation dose. When measured with the RMS only, it is at the level of 1.88, while for measurements including a control panel it is 3.14. This means that there is a very high proportion of neutron radiation in the total dose received by employees. The detectors used to detect gamma radiation do not register neutron radiation. Therefore, it is necessary to remember to equip the employees operating the cyclotron with neutron radiation detectors.

Exposures of personnel working at the production of radiopharmaceuticals (G3, N3), originating from

the cyclotron are at a low level. They receive 26% of the dose permissible for individuals without occupational exposure. The ratio of the dose from neutron radiation to the dose derived from gamma radiation for the personnel producing radiopharmaceuticals is at the level of 0.74. Here the exposure to neutron radiation in the total annual dose is decreased compared with the doses received by the cyclotron operating personnel. It should be remembered that in the production of radiopharmaceuticals, the radiopharmaceutical itself is the important source of exposure to ionizing radiation and the cyclotron is only a small part of it.

The radiation doses measured by the RMS system are the upper values of doses received by the personnel of the cyclotron operation and production of radiopharmaceuticals (provided that all activities are performed in accordance with applicable procedures). It should be remembered that every reduction of the employee's time of presence within the exposure area reduces the radiation dose such employee receives. Each employee is equipped with an individual radiation dose meter that allows to precisely determine his or her exposure level. Additionally, the cyclotron operation personnel present in the control room as well as the radiopharmaceutical production workers present in the production hall are equipped with individual electronic dose meters that allow to determine the amount of the absorbed gamma radiation immediately after work in the exposure area. Electronic detectors allow to monitor the level of doses absorbed by employees during specific procedures in the exposure area.

Values obtained from individual electronic detectors of gamma radiation indicate that cyclotron operation personnel performing routine tasks receive a dose of 0.23 mSv per y. This value remains in the range from 17% (measurement with RMS only) to 32% (measurement with the FH 40 G-10 detector) of doses presented in Table 3. Such a radical reduction in the operation personnel exposure in comparison with the RMS system results from the lack of the need to stay in front of the computer controlling the cyclotron (it is possible to observe the screen of the control monitor outside the cyclotron control room). Such a possibility significantly reduces personnel exposure. In the case of radiopharmaceutical production workers, the dose obtained from individual electronic gamma ray detectors is at the level of 0.27 mSv per y. This is a dose 80% greater than the dose registered by the RMS system. However, it should be kept in mind that the dose value presented in Table 3 refers only to employee exposure during the cyclotron operation. The personnel of the production laboratory perform most of the activities with the produced isotope, which in their case is the largest source of exposure. During cyclotron operation, activities related to the acceptance of the isotope to the laboratory are per-



formed. The comparison of readings from individual detectors and from the RMS system clearly shows that the main source of exposure for this group of employees, who perform activities in the production laboratory, is the radiopharmaceutical obtained in the production.

Unfortunately, the center's employees are not covered by individual dosimetry in the scope of neutron radiation. This is the case with a very large number of cyclotron laboratories producing radiopharmaceuticals for PET diagnostics. The analysis shows that it is a significant source of employee exposure. Further analysis of the distribution of neutron radiation doses around the accelerators used in laboratories and analysis of the risk of negative impact of this radiation on staff should result in the introduction of unambiguous legal regulations requiring the use of neutron dosimetry in such laboratories. Allowing to estimate the total dose received by staff, because it should be remembered that the exposure of staff to ionizing radiation is the sum of the components of exposure from all types of radiation.

## CONCLUSIONS

The level of exposure of employees operating the cyclotron and engaged in the production of radiopharmaceuticals is below the permissible radiation dose limits, i.e. 20 mSv per y. Cyclotron operating employees receive cyclotron doses within the category B exposure limits. However, due to the high probability of receiving high doses of radiation in the area of the cyclotron, they are classified to exposure category A<sup>(21,22)</sup>. For radiopharmaceutical production personnel, the doses from the cyclotron are very low, but for this group of employees, the main source of exposure is the radiopharmaceutical produced. In the area of radiopharmaceutical production, the probability of contamination is high, so this personnel is also classified to exposure category A. When estimating the dose, it should be remembered that neutrons have a very large share in the total dose of radiation from the cyclotron obtained by employees. Therefore, detectors should be used to assess exposure from neutron radiation. The RMS system is a quick and convenient tool for assessing employee exposure; however, it should be remembered that it overestimates the exposure of employees performing routine work. However, from the point of view of radiological protection, it is safer to overestimate the dose than to underestimate the employee exposure. Comparison of doses from the RMS system and individual dosimetry indicates a very good organization of work in the accelerator workshop. In fact, employees receive significantly lower doses than would result from environmental measurements (RMS system).

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