Survey of Radiation Exposure During Cyclotron Operation for PET Radiopharmaceutical Production at NINMAS

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ABSTRACT

Regular monitoring, proper shielding, and attention to safety procedures are all necessary for radiation safety in cyclotron facilities to reduce exposure and ensure regulatory compliance. This study investigates the radiation safety precautions taken at the National Institute of Nuclear Medicine and Allied Sciences (NINMAS) of Bangladesh Atomic Energy Commission (BAEC), during the operation of 18/9 MeV IBA Cyclone and synthesis of ^{18}F-2-fluoro-2-deoxyglucose (^{18}F-FDG).

Portable survey meters and fixed Geiger-Muller (GM) counters were used to measure exposed dose of radiation in highly hazardous locations such as the cyclotron control room close to the vault and hot cell close to the synthesizers. Measurements were thoroughly carried out before, during, and following cyclotron operations. The findings showed that the hot cell room experienced radiation levels of 2.3 µSv/h during the synthesis of ^{18}F-FDG, and the corridor vault experienced peak radiation levels of 2.0 µSv/h during the production of ^{18}F. There was still activity present since post-operation values were higher than the baseline. When handling ^{18}F-FDG, additional measurements at L-bench positions demonstrated the value of shielding and distance, with unshielded dose rates rising to 1.58 mSv/h.

Safety precautions including radiation workers distance guidelines, ALARA (As Low As Reasonably Achievable) principles, and real-time monitoring were implemented to provide radiation protection. The results highlight the necessity of constant radiation monitoring, sufficient shielding, and rigorous adherence to radiation safety procedures to reduce occupational exposure and preserve regulatory compliance in medical cyclotron facilities.

Keywords: Radiation Safety, Survey Meter, Geiger-Muller, Dose.

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INTRODUCTION

Positron Emission Tomography and Computed Tomography (PET-CT) imaging, a crucial diagnostic technique in Nuclear Medicine utilize 18F-2-Fluoro-2-deoxyglucose (^{18}F-FDG) that is produced by using cyclotron facilities. Medically important positron-emitting radionuclides including ^{18}F, 11C, and 13N are produced in this facility (1,2,3). The cyclotron operation room, hot cell room with synthesis modules, PET-CT areas, and Quality Control laboratories are the crucial areas in the facility used to produce ^{18}F-FDG. Each of these zones poses particular radiation safety risks that need to be carefully addressed to protect the health of the operators and the radiation workers. The ^{18}O (p,n)^{18}F nuclear reaction is used at our facility to create ^{18}F using the cyclotron (Model: 18/9 MeV IBA Cyclone) (4). This process produces both photon and neutron radiation, hence thorough shielding and safety precautions are required to reduce exposure dangers. Choosing the right shielding is essential when installing a cyclotron, especially to strike a compromise between radiation safety and operational effectiveness. The shielding designs used in cyclotrons are usually either vault-based or self-shielding. A self-shielded cyclotron eliminates the requirement for substantial external infrastructure by integrating retractable shielding into the device itself. Even so, a vault might be needed for self-shielded systems, albeit with walls that are thinner than those needed for a non-self-shielded cyclotron. On the other hand, vault-shielded cyclotrons depend on external shielding that is built into the structure of the building (5,6). Strong shielding is incorporated into the design of the 18/9 MeV IBA Cyclone to reduce radiation exposure, making it a flexible system for producing medical isotopes like ^{18}F (7). Following Atomic Energy regulatory standards, concrete with a density of 2.35 g/cm³ is used to construct the cyclotron vault's walls and ceiling. The concrete is thick enough to offer efficient shielding against gamma and neutron radiation (8). It is still necessary to conduct routine radiation monitoring in and around the cyclotron to ensure that exposure levels are maintained as low as Reasonably achievable (ALARA). Frequent radiation level monitoring is essential for locating high-exposure locations and facilitating prompt risk mitigation measures. This continuous monitoring helps Medical Physicists (MPs) and Radiation Control Officer (RCOs) protect operational personnel and the environment from excessive radiation exposure. The significance of shielding and monitoring in attaining a safe cyclotron facility design is highlighted by such extensive measures (9-12). Related findings have indicated that personnel can be protected during cyclotron operation by keeping radiation levels within allowable bounds by the implementation of suitable shielding and operational protocols (13). ^{18}F-FDG is further synthesized in hot cells, which are designed to encapsulate radioactive materials and protect operators from radiation exposure. However, handling highly active ^{18}F during synthesis can result in cumulative exposures of 4 to 10 µSv per synthesis, underscoring the importance of taking stringent safety precautions during these procedures. Quality control (QC) laboratories are essential for ensuring the efficacy and purity of synthesized ^{18}F-FDG. However, QC procedures involve handling radioactive samples, which can expose staff to radiation exposures ranging from 1 to 3 µSv per procedure. This highlights the importance of taking safety precautions to lower occupational doses (14).

Maintaining exposure levels to the all-radiation workers As Low As Reasonably Achievable (ALARA) requires thorough radiation monitoring throughout the whole facility (15). Potential hazardous locations can be efficiently identified and safety regulations can be adhered to by putting in place real-time monitoring devices and performing routine radiation surveys. For instance, studies have shown that maximum dose of radiation is often observed near irradiated targets, emphasizing the need for targeted monitoring in these regions (13). The operation of cyclotron facilities for ^{18}F-FDG production required various aspects, each with distinct radiation safety considerations. Through diligent monitoring, robust shielding, and adherence to established safety protocols, it is possible to minimize radiation exposure to personnel, thereby ensuring a safe working environment in compliance with regulatory standards.

MATERIALS AND METHODS

This study was carried out at the National Institute of Nuclear Medicine and Allied Sciences (NINMAS) facility of Bangladesh Atomic Energy Commission, which has three Synthera® auto synthera synthesis modules and an 18/9 MeV IBA Cyclotron. Production of ^{18}F and the subsequent synthesis of ^{18}F-FDG are the main uses for these units. Additionally, we synthesised ^{18}F-NaF and 11C-methionine several times in our facilities. But only ^{18}F-FDG is commercially supplied to all PET-CT centers in Dhaka. To guarantee radiochemical purity and efficacy, quality control of the synthesized radiopharmaceuticals was carried out in a special Quality Control (QC) facility. The QC laboratory is equipped with a gas chromatograph (Shimadzu GC-2010 Plus) for residual solvent analysis, specifically ethanol and acetonitrile, a Multi-Channel Analyser (Elysa Raytest-Mucha, Germany) for gamma spectrum detection, an ISOMED 2010 Dose Calibrator (Dresden, Germany) for half-life calculations, and a Radio TLC Scanner (Elysa Raytest miniGita-Beta Positron Detector) for radiochemical purity evaluations using silica gel thin-layer chromatography. To ensure the safety and compliance

Figure 1: Portable survey meter used to monitor radiation doses.

of the produced ^{18}F-FDG, microbiological quality assurance is carried out utilizing specialised equipment for bacterial endotoxin testing (BET) and sterility evaluations.

To ensure real-time monitoring and continuous data logging, Geiger-Muller (GM) counters and a portable survey meter (Model No. 6150 AD 5/H) were used to collect exposed radiation doses in a systematic manner.

These GM counters were installed in two places (Close to the the hot cell and cyclotron operation room) where the dose of radiation may be higher compared to any other locations.

Figure 2: Fixed GM counter in the hot cell room.

Figure 3: Fixed GM counter installed at the cyclotron operation room

All survey meters were zeroed in a low-background radiation location to establish baselines and calibrated to assure accuracy prior to beginning the measurements. During data collection, operators minimized personal exposure to radiation by adhering to safety protocols of our institute like wearing pocket dosimeters and taking measurements from at least 01 meter distance. The cyclotron operation and control area, the vault room corridor, the hot cell room corridor, the cassette conditioning room, the quality control room, the car parking area, and the 01-meter distance from the hot cell were the key locations throughout the facility where measurements were taken using the portable survey meter. Three distinct sets of data were collected: before, during, and after the operation was performed. The L-bench utilized in the PET-CT suite and the L-bench placed in the hot cell room were the sites of further measurements.

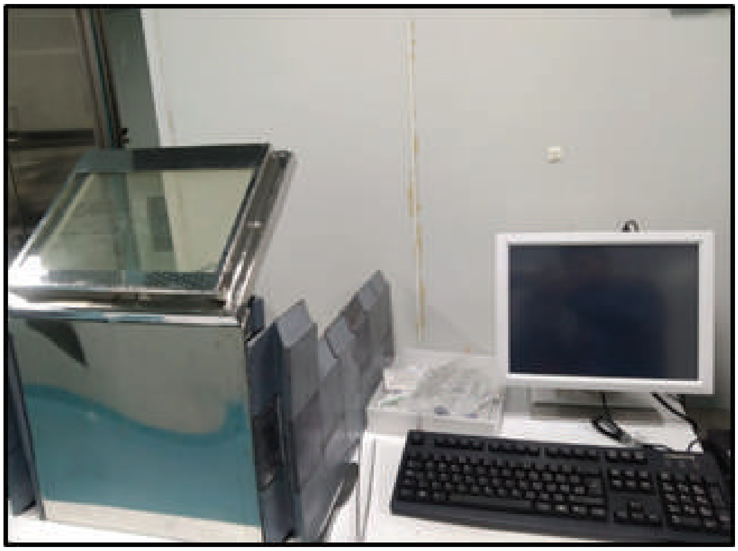

Figure 4: L-Bench utilized at the hot cell room.

In order to reduce operator exposure, portable survey meters were held at arm's length. To ensure consistency, readings were standardized at a height of one meter above the ground.

Continuous radiation level tracking was observed by fixed GM counters in the cyclotron and hot cell operation rooms, which recorded exposure peaks and variations in real time. The data was analyzed to determine radiation levels in various areas and to check measurement consistency between portable and stationary counters. Additionally, this study made sure that ALARA (As Low As Reasonably Achievable) principles and regulatory safety criteria were followed. The thorough methodology made it easier to optimize safety procedures throughout the facility and offered a reliable assessment of radiation exposure patterns.

RESULTS

The exposed dose of radiation measured at different sites during various operating statuses using a portable survey meter is shown in Table 01. During the production of ^{18}F by cyclotron in the control room and in hot cell room at the time of synthesis of ^{18}F-FDG from 18F the radiation exposure increased most significantly. The hot cell chamber had the highest exposure level during operation (2.30 µSv/h), followed by the hallway vault (2.0 µSv/h). Radiation exposure decreased at all sites after the competition of synthesis, however it was still quite higher than before, indicating that there was still some activity, especially in the hallway vault and hot cell room. Effective radiation containment and shielding was seen by the low exposure levels in the parking lot.

Table 1: Average exposure of radiation by portable survey meter at different locations.

Operational status (µSv/h)	Control Room (µSv/h)	Corridor Vault (µSv/h)	Hot cell room (µSv/h)	Corridor Hot cell (µSv/h)	Conditioning Room (µSv/h)	Quality Control room (µSv/h)	Car parking area (µSv/h)
Before	0.11	0.18	0.12	0.11	0.12	0.13	0.11
During	0.61	2.0	2.30	0.12	0.78	0.56	0.45
After	0.25	1.2	1.52	0.12	0.65	0.45	0.31

The exposed radiation doses in the control and hot cell rooms were also determined using a GM counter, and the results are shown in Table 02. The findings indicate that exposure increased significantly during synthesis of ^{18}F-FDG, peaking at 3.0 µSv/h in the hot cell chamber. In comparison to baseline, post-operation exposure levels were lower but still higher, with the hot cell room recording 1.6 µSv/h and the control room recording 0.2 µSv/h. The data observed in GM counter is similar to the found data by using portable survey meter.

Table 2: Average exposure of dose measured by GM counter

Operational status	Control room (µSv/h)	Hot cell room (µSv/h)
Before	0.1	0.2
During	0.6	3.0
After	0.2	1.6

The radiation exposure levels when handling 260 mCi of ^{18}F-FDG in the hot cell L-bench are shown in Table 03. To assess exposed radation levels, recordings were made at various locations and distances. The top surface showed a noteworthy dosage rate of 1.58 mSv/h at no shielding, while the left and right side had also the greatest dose rate without shielding (1.58 mSv/h). The dose rates significantly decreased at a distance of one meter, demonstrating the value of distance as a protective factor. This emphasizes how crucial it is to have the proper shielding and operating distance when handling high-activity radiopharmaceuticals to reduce radiation exposure.

Table 3: Cyclotron Hot-cell L-Bench handling with 260mCi ^{18}F-FDG

Sl. No.	Position	Dose at no distance	Dose at 01-meter distance	Dose at no shielding
1	Top	1.58 mSv/h	286 µSv/h	-
2	Front	96 µSv/h	60 µSv/h	-
3	Left	66 µSv/h	56 µSv/h	1.6 mSv/h
4	Right	80 µSv/h	60 µSv/h	1.58 mSv/h

The exposed radiation doses recorded while handling 20 mCi of ^{18}F-FDG in the PET CT L-bench are compiled in Table 4. At a 1-meter distance, the top surface had the maximum dose of 100 µSv/h, although the left and right surfaces had higher readings of 120 µSv/h and 110 µSv/h, respectively. Both the left and right sides reported 250 µSv/h and 220 µSv/h without shielding, highlighting the significance of shielding barriers with lead block when handling radiopharmaceutical (^{18}F-FDG) in PET-CT facilities.

Table 4: Exposed radiation at PET CT L-Bench handling with 20 mCi ^{18}F-FDG

Sl. No.	Position	Dose at no distance (µSv/h)	Dose at 01-meter distance (µSv/h)	Dose at no shielding (µSv/h)
1	Top	7	100	-
2	Front	5	8	-
3	Left	6	120	250
4	Right	6	110	220

DISCUSSION

The analysis indicates a significant increase in exposure to radiation during operations of the cyclotron for the production of ^{18}F-FDG particularly in the corridor very close to the Vault and Hot cell room locations, which is consistent with the findings of similar studies were observed elevated radiation levels in cyclotron unit during operational periods (16). Some locations, such as the Hot Cell room and Corridor Vault, continue to have elevated levels of radiation even after procedures ended. The activation of materials used in wall or other barriers and remaining radioisotopes are probably the causes of this remaining activity (17). Tables 03 and 04 demonstrate exposed dose significantly drops as one gets farther away from the source.

. In this case, the dose drops from 1.58 mSv/h at no distance to 286 µSv/h at 1 meter at the Top location in Table 3. This highlights the significance of keeping a safe distance to reduce exposure and is an example of the inverse square law in radiation safety (18). This finding showcases the importance of shielding for

radiation protection. The dose found in Table 04 for the left position without shielding is 250 µSv/h, which is much greater than the readings made with proper shielding made by lead blocks.

This emphasizes the important for facilities handling radioactive elements to have the right shielding materials and structures (19). Based on the working location and how the facility is functioning, employees in these settings may be exposed to different radiation levels. To make sure exposures stay under allowable levels, safety procedures include controlled access during radiation peak times and routine monitoring must be implemented (20). The design of the building wall and barriers, which includes sufficient shielding and well-placed control rooms and work areas, is crucial in reducing radiation exposure and marked as a supervised area. Those areas are restricted for entries. The International Atomic Energy Agency (IAEA) guidelines provide important information regarding the best way to design facilities and defend against radiation (21). It is very important to ensure that radiation exposure limits meet international guidelines. The ALARA (As Low As Reasonably Achievable) principle is emphasized in the International Commission on Radiological Protection (ICRP) recommended dose limits to protect the public and employees. Frequent radiation level monitoring and equipment maintenance are essential for quickly identifying and resolving any abnormalities. This study contributes to preserving a secure workplace and avoiding needless exposure.

CONCLUSION

The findings represent the importance of implementing comprehensive radiation safety measures in this facility handling ^{18}F-FDG. Regular monitoring, effective shielding, adherence to ALARA principles, and thorough training of personnel are essential to minimize radiation exposure risks. Future studies should focus on optimization of these safety protocols and exploring advanced technologies to further enhance radiation protection in medical and research facilities.

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