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ORIGINAL ARTICLE

Radiation dose management of ^{18}FDG for occupational workers and comforters

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Abstract

Objective The study details our work in managing radiation doses to our workers and comforters when dealing with ^{18}F-FDG under the ALARA principle.

Methods Pakistan's first PET-CT suite with on-site cyclotron was designed under the guidelines of AAPM Task Group Report #108 in 2009. Concrete, Perspex and lead were used as shielding materials to justify cost and space availability. The controlled areas were designed for permissible dose limit of ≤ 2 μSv/hr. The staff members who have direct contact with ^{18}F-FDG are given thermolumiscence dosimeters to record their monthly whole-body and extremities doses.

Results Once operational, the maximum prevailing exposure is ≤ 10 μSv/ hr in FDG Synthesis unit at 5 Ci. The prevailing exposure in the PET-CT Console and injection room is ≤ 2 μSv/ hr, Pre-scanning room ≤ 5 μSv/ hr, post scanning room ≤ 0.2 μSv/ hr; cyclotron vault surrounding is ≤ 0.1 μSv/ hr. Nursing staff, injecting and dispensing ^{18}F-FDG are rotated once in a week to inject ten patients per day/week using lead shielding to cover syringe, lead bricks and movable trolley. A short interaction between the patients are the technologists reduces the technologist's dose to ≤0.6 mSv/ month (≤17 mSv/month). Three radio-chemists produce up to 5 Ci radioactive ^{18}F-FDG on a daily basis in an automated shielded synthesis unit. The average radiation dose for each radiochemist is ≤0.7 mSv/month (≤27 mSv/month). Medical Physicists and cyclotron engineers receive ≤0.5 mSv/month (≤ 10 mSv/month). The comforters receive ≤1.5 mSv/scan recorded by the electronic pocket dosimeter (EPD). Each patient is released when the radiation exposure is reduced to ≤20 μSv/hr at 1 meter.

Conclusion In the last five years (2009 to 2013), 10,000 patients were scanned with an average of 330 MBq injected dose. The maximum average dose received was 4 mSv/year for some members of nursing staff and radiochemists, whereas the least average dose of 1 mSv/year was received by technologists and the rest of the staff received doses ≤1 mSv/ year.

Key words: *^{18}F-flourodeoxyglucose, positron emission tomography, radiation dosimetry, radiation protection*

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Introduction

Hybrid imaging has unleashed the anatomical and physiological details in single-bed scanning. The hybrid machines uses photons and x-rays of different energies to produce emission and transmission scans separately, and the modern computer algorithms aid the user to merge both images to observe fused appearance [1]. Positron Emission Tomography (PET) has been leading the nuclear medicine utility by utilizing radioactive ^{18}F-FDG (F-18) as the most commonly used radioactive material to perform emission scanning. The addition of Computed tomography (CT) aids to provide anatomical details by adding transmission scan. The composite (PET-CT) therefore leads towards a hybrid image for accurate diagnosis and disease staging [2]. The utilization of both photons and x-rays has no doubt, enhanced the radiologist's vision; however, it has created challenges for the safety of staff, comforters and general public for this hybrid modality.

Shaukat Khanum Memorial Cancer Hospital & Research Center (SKMCH&RC), Lahore, Pakistan, is the first facility in the country to establish a PET-CT & Cyclotron with an on-site Radiopharmacy. Being the only facility in Pakistan, we have a heavy load of patients especially from oncology referred from throughout the country. This patient demand provided the impetus to establish another PET-CT centre, the third of its kind in Pakistan, at Shaukat Khanum Diagnostic Center (SKDC), Karachi, Pakistan. Both PET-CTs are geographically far apart with a distance of 1000 km in between. At present, there are a total four PET-CTs in the country. We have scanned more than 10,000 patients at SKMCH&RC, Lahore, since November 2009. whereas 600 patients have been scanned at our Karachi PET-CT centre since December 2012. We produce at least five Curie (5 Ci) ^{18}F-FDG from the cyclotron with at least average 3.5 Ci ^{18}F-FDG (average yield of 60%), for 5 days in a week.

The study aimed at documenting the radiation dose received by all radiation workers involved in the production, synthesizing, dispensing, injecting and performing patients scanning with ^{18}F-FDG. We also considered the situations when automated machines fail and the staff has to interact with the radiation manually. We use TLD badges along with EPDs for the whole-body dose measurements along with TLD rings for the extremities dose measurements. The results mentioned in this paper are from EPDs.

There are three major activities which expose the staff directly to radiation including: 1) radiotracer production and synthesis, 2) quality assurance and 3) injecting the patients with ^{18}F-FDG. The fourth important factor to be considered is the radiation dose to patient's comforters [3].

The production of ^{18}F radionuclides is from medical cyclotrons located near PET-CT scanners owing to shorter half-life of cyclotron produced radionuclides used for PET. Fluorine-18 (^{18}F) with half-life of 110 minutes, is one of the cyclotron produced radiotracers obtained from proton bombardment of Oxygen [4]:

$$^{18}O \quad (p,n) \quad ^{18}F$$

The emission scan from PET is primarily owing to pair-production in which minimum required energy is 1.02 MeV. In both the cases, radiation exposure cannot be completely ignored. Fluorine-18 (^{18}F) emits β+, with average energy of 1.02 MeV, satisfying the basic condition for the occurrence of pair-production [5]. ^{18}F is a neutron deficient radionuclide that decays both by electron capture (3%) and positron emission (97%) as shown in Figure 1. The decay data of ^{18}F is shown in Table 1.

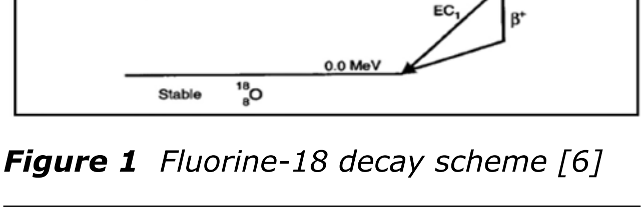

Figure 1 *Fluorine-18 decay scheme [6]*

Table 1 *^{18}F decay table [6]*

Radiation Emission	**Mean Number / Disintegration**	**Mean Energy Particle (MeV)**
Beta Plus	0.97	0.2496
Annihilation Radiation (ϒ)	1.94	0.511

The interaction of the positron with an electron results in the production of two nearly anti parallel 511 keV annihilation radiation photons with total e abundance of 194% (2 x 97%) [6].

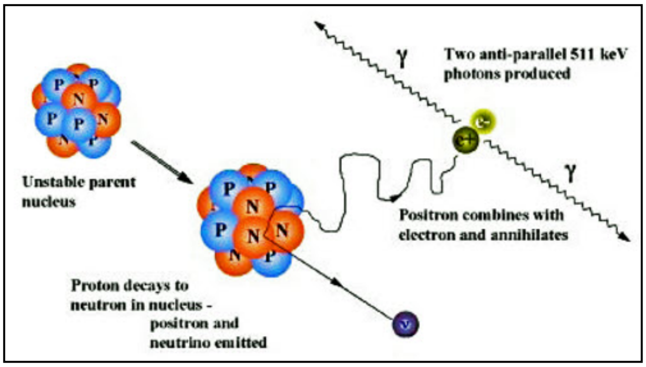

Figure 2 *Production of 511 keV photons [6]*

The radiotracer is then tagged with carrier "glucose" to convert it into ^{18}F-FDG or 2-deoxy-2-[18F] Fluoro-D-glucose. It was first synthesized by Brookhaven chemists in 1976 by the researchers at the US Department of Energy's Brookhaven National Laboratory [7]. The process of tagging is performed by a team of radiochemists/radiopharmacists within a controlled automated synthesizer. The automated synthesizer is enclosed within heavy lead linings to protect radiation workers. The next step is to perform quality assurance of ^{18}F-FDG for radionuclide and radiochemical impurities. Following successful quality assurance the radiochemists/ radiopharmacists dispenses the doses for patients either manually or through automated processes. The ^{18}F-FDG is then injected into the patients before performing emission scanning. The average adult dose is 330 MBq.

The specific γ-ray dose constant, defined as the dose rate from 1 MBq of an isotope at a distance of 1 m, is 18.79E^{-5} [mSv/h]/MBq. The narrow-beam half-value layer for 511 keV photons is 4.1 mm and the practical broad beam half-value layer allowed for Compton scattering is > 5 mm [3]. The radiation exposure from any radionuclide can be calculated by using specific gamma radiation constant (Γ), equation 1 [8]:

$$\text{Exposure Rate} = \Gamma A/d^2 \qquad [1]$$

The effective dose in Sievert can also be calculated by [9] the summation of the product of the dose to each organ (H_T) and its respective weighting factor (W_T), equation 2:

$$E = \Sigma\, W_T\ .\ H_T \qquad [2]$$

The American Association of Physicists in Medicine (AAPM) Task Group Report #108 enabled us to calculate the shielding for the PET-CT facility. The prevailing radiation exposure in all areas with maximum 5 Ci activity in Cyclotron, 500 mCi ^{18}F-FDG in injection room, the radiation exposure in PET-CT from 511 keV and CT scanner (130 kVp and 100 mAs) is described in Table 2.

Table 2 *Prevailing radiation exposure (μSv/hr) in controlled areas*

Controlled Area	**Exposure**
Cyclotron Operator Room	2
Synthesis & dispensing Unit	10
QA Lab	2
Injection Room	4
PET-CT Console	2

Materials & Methods

This prospective study involved 2 cyclotron engineers, 2 radiochemists, 1 radiopharmacist, 2 medical physicists, 6 PET-CT technologists, 6 nursing staff, 10 comforters for adults patients and 10 comforters with paediatric patients (patient ages ranging 1 to 5 years) dealing directly with the patient following discharge. Mirion Electronic pocket dosimeter was used for individual dose exposures whereas Automess AD/500 Survey Meter was used to measure the prevailing radiation exposures within the facility.

The SKMCH&RC at Lahore houses one IBA cyclotron (18 Mev) with two targets, one large and one medium target, capable of producing a maximum of 7 Ci of ^{18}F. The radiochemistry section has a pair of two automated IBA ^{18}F-FDG synthesis units with maximum of 63 mm lead lining along with automated. There is one automated dispensing unit but no manual dispensing unit. The PET-CT camera is a Philips time-of-flight (ToF) PET with BGO crystals coupled with a 16-slice CT scanner.

The dedicated injection room receives an activity of up to 500 mCi in a dedicated shield container of 2.5 cm of lead thickness with a weight of 9.7 kg capable of holding a maximum of 1.5 Curie of ^{18}F-FDG [10]. Nursing staff utilizes movable trolley with a 1-inch thick lead panel (22" width x 19" height) and 14 mm syringe cover (Z PET) and 0.64 cm thick lead-lined syringe holder to transport ^{18}F-FDG dose per patient. The patient is injected manually using a manual injector with the rotation shield with 1-inch (2.5 cm) thick lead and a plunger made of 0.5-inch (1.25 cm) thick tungsten. Lead bricks (3-inch thick) and lead L-shields (2.4-inch thick) provided the lead shielding in front and at the base to enclose the bulk activity and dose calibrator chamber. We do not use any automated system to dispense unit dose from the bulk activity.

All controlled areas are continuously monitored with MIRION probes capable of continuously measuring both γ-ray and neutron exposures.

Automated Operational Activities

The production, synthesis, dispensing and injection of ^{18}F-FDG involves a number of automated equipment. The "normal routine" implies that all the automated machines are working without any error so there is no human interaction or any manual intervention. This routine also implies that there is no nurse or technologist patient comforter involved except for injecting and patient positioning. The average radiation dose for cyclotron engineers and radiochemists/radiopharmacists is worthy of consideration as a proof of the credibility of the equipment shielding and rationality of the rotational plan based on occupancy factor. As we do not use any automated equipment in the injection room, there is no equipment malfunction involved.

Manual Operational Activities

The automated systems caters for proper preventive maintenance and swift replacement of any defective parts. However, being in third world country time bar and lack of technical skills prolong the availability of new parts whereas shrewd diagnosis does lack owing to shortage of skilled man power.

The preventive maintenance of the equipment is designed on quarterly basis in a year. The main challenge is to perform cyclotron maintenance where there is heavy radiation exposure, both from neutrons and gamma rays, from cyclotron target and associated pair of Dee. The first day of preventive maintenance is lost to wait for the decrease of radiation exposure. The occupancy time is then requested from the engineers to perform work with open cyclotron after measuring radiation exposure with the help of survey meter on the surface of the targets and core of the cyclotron. Two personnel work one by one to fix the problems. This is a planned radiation exposure; however, we do face problems when ^{18}F is stuck in the tubing leading towards radiopharmacy. The identification of the point where the activity is stuck and then it is released really poses a risk of heavy exposure to the cyclotron engineers. However, instead of manually handling, the first option is to re-push the activity to the radiochemistry by increasing the pressure of Helium gas. The preventive maintenance provides 20 μSv exposures for 4 hours of work; however, exposure from tubing where up to 5 Ci of ^{18}F is stuck is in Sieverts, therefore the team waits till the activity reduced to one-tenth.

The radiopharmacy houses two automated IBA synthesizers with one automated dispensing unit. Sometimes the system fails to process automated tagging, and therefore manual intervention by the radiochemist become mandatory. Radiochemist/ pharmacist deals with ^{18}F by opening the hot cells to rectify the problem. The occupancy and activity contained within the system is considered to calculate the expected radiation exposure especially to extremities. The first choice is to wait till the activity is reduced to such a level that the absorbed radiation dose does not exceed the daily dose (0.68 μSv). The mean radiation exposure received during such problem is always greater than the decided exposure and it is 60 μSv/day. The radiation worker is then relieved from radiation area and further radiation dose is calculated to rotate them in the less radiation areas (e.g. in conventional nuclear medicine dealing with ^{99m}Tc). This balances the monthly dose limits. The second threat to radiopharmacy radiation workers arises when automated dispensing unit (robotic arm) fails to respond. A contingency plan has been developed for radiopharmacy where they can deal with only 1 Ci (one Curie) ^{18}F (or ^{18}F-FDG). Two radiochemists are required to handle the synthesizer and manual dispensing separately, with a resultant individual radiation dose exposure of 22 μSv/interaction with maximum of 1 Ci ^{18}F/^{18}F-FDG. The average time to handle the synthesizer is 10 minutes and manual dispensing takes only two minutes.

Nursing staff receives bulk activity of 500 mCi in 2.5 cm of lead thickness shield capable to contain up to two Curie ^{18}F. The staff uses L-shield and 3 inch thick lead bricks to gaurd against radiation exposure. Each nursing staff member is rotated once in a week to inject ten adult patients. The average dose for each adult patient is 330 MBq through manual dispensing of ^{18}F-FDG. The steps involved include drawing up the dose, measuring it in the dose calibrator, adjusting the dose, placing it in lead-lined syringe carrier, moving the dose to the patient on a lead lined trolley, and injecting and flushing the dose with normal saline.

There are problems mosly associated with uncooperative, young and old aged patients. Our policy requires two comforters when performing PET-CT scanning in this group of patients. The first comforter accompanies the patient from the injection to the scanner room and the second comforter, if really needed, accompanies the patient during both emission and transmission scanning. The comforters should be adult and non-pregnant. They are given an electronic pocket dosimeter along with special set of instruction to follow time, distance and shielding instructions where applicable. The maximum average dose received by comforters from a adult patient, in first phase, is 45 μSv whereas the maximum average dose received in the second phase is 1.05 μSv. The dose has been reduced by educating the patient's attendants to keep at a distance from patient and stand near the console wall when performing CT. During the second phase, whenever possible the policy is to discourage patient comforter and only rarely do they accompany the patient. No radiation worker is allowed to be the voluntary comforter for the patient. On discharge, the patients are given instruction to follow for next 5 hours to sit at least one meter away from children and pregnant women.

Results

In the normal operational activities, the radio chemist/radiopharmacist receives an average gamma radiation dose of ≤0.7 mSv/m (≤20 mSv/m), nursing staff injecting at least ten patients per rotation once in a week with average of 330 MBq adult dose receives ≤0.75 mSv/m (≤27 mSv/m), cyclotron engineers receive ≤0.5 mSv/m (≤10 mSv/m), medical physicists receives ≤0.5 mSv/m (≤2 mSv/m) with the nuclear medicine physicians receiving up to ≤0.2 mSv/m (≤2 mSv/m).

The 5-years radiation doses pattern projects that average highest dose is received by radiochemist/pharmacist during normal circumstances (0.7 mSv/m whole-body and 20 mSv/m extremities) and also in manual handling (22 µSv/Ci whole-body and 65 µSv/Ci from extremities). The nursing staff are in the second place, with average absorbed dose (0.75 mSv/m whole-body and 27 mSv/m extremities). The cyclotron engineers are in the third place, with the average radiation dose being 0.5 mSv/m and 10 mSv/m for whole-body and extremities respectively during normal condition excluding 22 µSv/4-hour during preventive maintenance in each quarter. The controlled radiation doses (0.6 mSv/m whole-body and 17 mSv/m extremities) to the technologists protects them from direct radiation exposure from ^{18}F-FDG when positioning patients and the small scattered radiation dose (1 µSv/hr) from CT owing to alternative month rotation. Medical Physicists' exposure can be up to 0.5 mSv/m as they have to perform quality assurance when they directly deal with ^{22}Na sources and make phantoms with ^{18}F-FDG . The annual average dose for the PET-CT staff is 4 mSv whole-body and 32 mSv for extremities, if we consider all workers for a period of five years. However, this exposure is quite lower than annual recommended dose limit. The nuclear physicians are receiving the radiation dose that is also negligible. Table 2 describes radiation doses for all staff under the conditions of "normal routine".

Table 3 *Average radiation dose for five years from ^{18}F-FDG under normal operational activities*

Modality	**Average γ Radiation Dose (mSv/month)**	**Extremities Radiation Dose (mSv/month)**
Radiochemist	0.70	20
Nursing Staff	0.75	27
Cyclotron Eng	0.50	10
Technologist	0.60	17
Physicist	0.50	2
Physician	0.2	1

Table 4 *Average radiation dose for five years from ^{18}F-FDG under manual operational activities*

Modality	**Average γ Radiation Dose (mSv/month)**	**Extremities Radiation Dose (mSv/month)**
Radiochemist	0.8	28
Nursing Staff	0.75	27
Cyclotron Eng	0.52	10
Technologist	0.60	17
Physicist	0.50	2
Physician	0.2	1

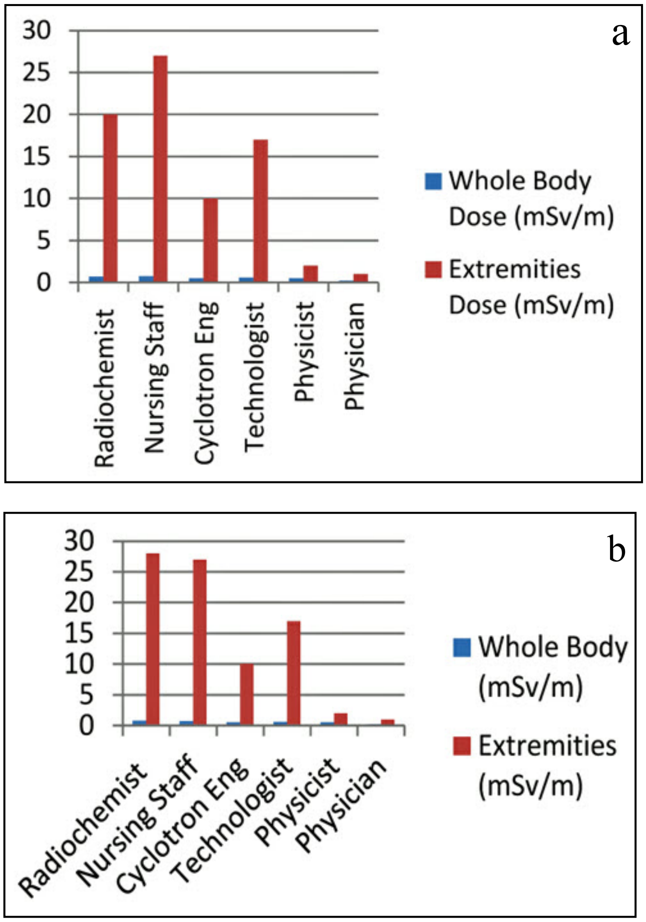

Figure 3 *Radiation doses received by different staff groups during normal operational (a) and during manual operational activities (b)*

Discussion

Radiochemists bear highest radiation exposure owing to their close contact when synthesizing and dispensing ^{18}F-FDG . The prevailing exposure within the synthesizer and dispensing room is even higher because of heavy lead shielding within the automated units. The manual handling of ^{18}F-FDG is also a risk without manual dispensing unit. Nursing staff make very close contact with ^{18}F-FDG for each patient either with automated dose adjustment systems or with manual injectors. The nursing staff I are the only staff who are in the close proximity of the patient during injection or just after injection. Cyclotron engineers enjoy a safer environment during daily production as cyclotron control rooms are well shielded and away from cyclotron bunkers; however, preventive maintenance entails a significant radiation exposure owing to working with the open cyclotron and target cleaning. The radiation dose to the technologists is also on the safer end with at least 10 patients per day and one month (20 working days) rotation on an alternative month. However, patient positioning of some uncomfortable patients is a challenge for them to justify their dose limits.

The average dose per injection received by nursing staff is 2μSv. A strict regulation is that each nursing staff member shall be rotated once in a week to inject ^{18}F-FDG as they also perform duties either in Radiology or in conventional Nuclear Medicine where they inject ^{99m}Tc and dispense and provide both in-patient and out-patient based radioiodine (^{131}I) therapies. However, duties are scheduled with respect to activity handled per week.

The cyclotron engineers are in the third place, owing to strict involvement of the RPA in decide their occupancy when dealing with open cyclotron.

PET-CT technologists are rotated for a month. One technologist is appointed from Radiology and the other technologist is assigned from Nuclear Medicine. Both of these technologists interact with radiation in their duties while performing scanning on radiological machines or SPECT/CT or gamma cameras. The goal of dose minimization for technologists is met by minimizing direct interaction between staff and patient through CCTV monitoring and communication. Technologists can watch the injected patient in the pre-scanning room and they can also listen to the patient through two-way communication system. Once the patient scanning starts, technologist communicates with the patient using the installed speaker. We have drawn two types of lines on the floor. The "red line" guides the patient toward PET-CT scanner via the patient dedicated toilet. The patient follows the red line to reach the PET-CT machine whilst the technologist is observing his movements. This decreases the direct interaction of the technologist with the patient while walking to the scanner. The next step is the positioning, where the technologist properly positions the patient within a couple of minutes using positioning devices and provides a set of instructions. At completion of the scan, the technologist announces to the patient instructions to follow the "green line" to move to the post-scanning room, from where he is discharged at an average duration of 45 minutes or once the radiation exposure from the patient is ≤20 µSv/hr at one meter. The average radiation dose received by a technologist per day is 2 µSv from 10 patients when normally positioning patients. However, the maximum exposure when dealing with some difficult patients like paediatric patients or some old patients need more attention or where the technologist needs to be vigilant is ≤5 µSv. This is because there is minimum period of 45-60 minutes between the injection and the scan, which allows the radiation exposure to decrease by excretion and decay of ^{18}F-FDG.

The radiation dose to the medical physicists accrues purely from performing quality assurance tests with ^{22}Na on a daily basis and performing SUV validation once in a week. The medical physicists receive ≤0.5 mSv/m exposure with a negligible extremity dose of 2 mSv/m. However, when a medical physicist is also performing extra duties as a Radiation Protection Officer (RPO), they may receive a dose above a beyond this value depending on the type and nature of the incidence. There has however been no documented incident involving major spillage or a radiation accident in our facility in the last 5 years.

The radiation doses to the nuclear physicians are also negligible as the reporting room and the clinical areas are located away from the controlled radiation areas. Therefore there is no direct contact between the nuclear medicine physicians and the injected patients. However, in case of emergency when physician assistance is necessary, the dose is measured by RPO on the basis of the occupancy time. The nuclear physicians in general receive minor doses. One such dose incident was recorded when a patient was shifted to ICU after scanning. The average radiation dose received by the physician was <4 µSv for his 10 minute contact.

Medical Physicists and nuclear physicians do enjoy the liberty from median level exposures owing to a minimal interaction with controlled radiation. The comforters exposure is both need- and passion-based since people tend to behave emotionally when they accompany their near relatives. However, division of comforter in two phases has really saved them from unwanted absorbed radiation doses. It is worthwhile to note that the radiation exposure from CT scanner have been ignored owing to negligible exposure in the console room; however, this exposure is considered only for the comforter in the second phase.

The Pearson correlation between the whole-body doses (r=0.985) and extremities doses (r=0.9658), reflects a strong correlation between the exposure received during automated and during manual dispensing. This also shows the authenticity of safety measures for radiation workers.

A PET-CT facility utilizing ^{18}F-FDG, poses no major threat to the staff working with medical radiation exposure, where there is proper training in place, automated and manual synthesizer/dispensing units are available, there is adequate number of trained staff, practical local rules are instituted and adhered to, and mathematically calculated expected radiation doses are provided during emergency handling. The average 4 mSv/month dose for a period of five years with 10,000 scans proves the efficacy of our radiation safety measures and helps ward off unjustified fears and uncertainty regarding radiation exposure in our radiation workers. The annual medical surveillance of our radiation workers revealed no injury from radiation. We are however going to install a manual ^{18}F-FDG dispensing unit this year to avoid radiation dose to radio-chemist which will further decrease the average annual dose of the staff.

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