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Radiation Levels Measurement at Workplace of Cyclotron-PET/CT Facilities in Karachi using TLD Dosimeters

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Abstract

A 'Cyclotron' is a proton particle accelerator, broadly used for short-lived isotopes (like F-18) production for imaging in radiation oncology. In Pakistan, Fluorine (F-18) is being produced by the cyclotrons installed in various hospitals. F-18 emits two gamma photons through the annihilation phenomenon, having 511 keV energy each. F-18 has converted into (18F) Fluorodeoxyglucose (FDG) through the synthesis process. This high-intensity gamma photon may be dangerous to radiation workers if radiation safety regulations are not followed. A study was conducted for the measurement of ambient radiation levels in the controlled areas and supervised areas of cyclotron facilities using Thermoluminescent Dosimeters (TLDs). The results obtained from TLDs were formulated and evaluated. All measured values were meeting the criteria of classification of areas i.e., the radiation doses will receive greater than 6mSv/year in a Controlled area and the radiation dose will receive greater than 1mSv/year in a Supervised area as mentioned in Pakistan Nuclear Regulatory Authority (PNRA's) Regulations on Radiation Protection (PAK/904). It is concluded that all workers received radiation doses within limits and the facilities had implemented clause 26 of PNRA Regulations through effective shielding in the design of the cyclotron facilities, and dose monitoring. The effective implementation of PNRA regulations is verified through regulatory oversight and through such type of cross-verification in the country.

Index Terms: *Cyclotron, Fluorodeoxyglucose, Positron Emission Tomography, Radiation Levels, Thermoluminescent Dosimeters.*

I. INTRODUCTION

The usage of radionuclides in the field of biosciences is growing worldwide. The use of radionuclides in the physical and biological sciences can be classified into three; imaging, radiotherapy, and radiotracers. Positron Emission Tomography (PET) and Single-Photon Emission Computerized Tomography (SPECT) techniques are mainly adopted in imaging for diagnostic purposes. Most of the radionuclides used for diagnostic purposes have relatively short half-lives due to which, the low radiation dose will be received by patients in each study [1]. Generally, the radionuclides are produced in reactors through nuclear reactions or in accelerators through charged particle bombardment [2]. Technology advancements are helping the development of sophisticated machines which are enabling in minimizing radiation exposure to occupational workers as well as for patients. PET is one such kind of sophisticated technique, which is being used for several decades. It uses a cyclotron as a particle accelerator to produce short-lived radionuclides which are used in PET imaging. PET is primarily used for the diagnosis and monitoring of different stages of therapy.

A 'Cyclotron' is a proton particle accelerator, broadly used for short-lived isotope production for imaging purposes in nuclear medicine. The short-lived positron emitters have their own importance, especially in PET imaging namely, Fluorine (^{18}F), Oxygen (^{15}O) Nitrogen (^{13}N), and Carbon (^{11}C). The cyclotrons with proton energy less than 20MeV are used for the production of positron-emitting radionuclides. Such type of cyclotrons is usually installed within the facility/hospitals [3]. Currently, in Pakistan, only 18F is being produced in facilities/hospitals. The 18F is labeled with a glucose analog and converted into [18F] FDG. F-18 has a half-life of approximately 109 min (nearly 2 hours) and F-18 decays by positron emission and subsequently produces two gamma photons of energy 511keV energy via the annihilation process, which requires special consideration for occupational exposure [2]. The assessment of ambient radiation levels at the workplace describes the prevailing radiological condition that ensures the workplace is safe and satisfactory for occupational workers as per established guidelines by the regulatory authority. The radiation monitoring is normally planned, where occupational workers, patients, and the public is likely to expose to these ionizing radiations. The concept of classification of areas is defined as limiting radiation exposure of workers and the public. Keeping in view all the hazards of radiation exposure, PNRA defines criteria for the classification of areas in clause 26 of PAK/904 (Regulations on Radiation Protection), which requires the facility to demarcate areas as controlled areas and supervised areas with respect to radiation doses. In the controlled areas, the radiation dose will receive greater than 6mSv in a year, and in supervised areas in which the radiation dose will receive greater than 1mSv in a year by occupational workers [4]. The gamma photons and neutrons could be the main sources of radiation exposure to workers. Neutrons are produced in a nuclear reaction of 18O (p, n) 18F [1]. The concept of area classification is often covered during the facility's design phase. It is usually done through demarcation, the use of shielding calculations, designed features, and interlocks. The "As Low As Reasonably Achievable" (ALARA) principle of radiation protection must be followed by the radiation doses received from different ionizing radiation sources. The radiation protection programme is developed by facilities for the workplace and individual monitoring. The results of the monitoring must meet the dose thresholds of regulatory limits. The radiation doses that occupational workers received before or during work can be assessed indirectly through workplace monitoring, whereas individual monitoring provides direct radiation doses incurred by workers. For purposes of verification, workplace monitoring may be repeated at suitable intervals. In workplace monitoring, active TLD, etc., and passive radiation detectors (survey meters) are normally used [5].

Thermoluminescent Dosimeters (TLDs) were used in this study to confirm that clause 26 of PAK/904 was followed at cyclotron-PET/CT facilities (TLDs). Currently, six (06) cyclotron facilities are providing diagnostic services, all across Pakistan, out of which, four (04) are established in Karachi City. An author along with associates, evaluated ambient radiation levels in CIMol, PET/CT imaging center using TLD-100H and concluded that the radiation doses did not exceed the radiation dose threshold for the controlled area (5mSv/yr) and free area (0.5mSv/yr) as recommended by Brazilian regulations [6]. Researchers investigated ambient doses at the Nuclear Medicine Department using TLD-100 and TLD-900. The measured results of TLD-900 were found 25-45% higher than those of TLD-100. The results obtained from TLD-100 were representing real radiation exposure [7]. A study performed a radiation survey in and around a newly installed cyclotron before, during, and after operating the cyclotron using an ionization chamber counter and GM counter. The highest radiation level is observed in the cyclotron area. The radiation level was compared with Atomic Energy Regulatory Board (AERB), dose rate i.e., 0.25uSv/h. All the doses were well within the AERB dose limits [8]. Researchers conducted a study to assess technologists' whole-body dose and extremity exposure in the PET department using TLDs and Electronic Personal Dosimeters (EPD). The whole-body dose and extremity dose of technologists directly dealing with 18F-FDG in the PET center was lower than the maximum values allowed in European Directive EURATOM 96/29 05/13/1996 [9]. A Study utilized TLD-100, EPD, and GM dosimeter for estimation of radiation dose to staff and environment dose from [18F]-FDG in PET/CT and cyclotron center. The TLD and GM tube survey meters were used for environmental dose assessment. The doses were below the dose mentioned in the ICRP guidelines, which was achieved by minimizing time, increasing distance, and using proper shielding like injector shielding, etc., [10].

II. OBJECTIVE

The objective of this study is to verify the implementation of clause 26 of PAK/904 (Regulations on Radiation Protection) by measuring the radiation levels in controlled and supervised areas of PNRA-licensed cyclotron-(PET/CT) facilities at Karachi using TLD.

III. MATERIAL AND METHODS

A. Cyclotron and PET/CT Facility

Four medical facilities in Karachi City were chosen to take part in the current study. In Pakistan, mainly F-18 is produced for PET scanning. These selected facilities have two different kinds of cyclotrons, self-shielded and unshielded; the details are shown in table I, and figure I, respectively. Each of them has a predetermined QA/QC control that ensures the radioisotope manufacturing is both secure and of high quality.

Table I: Details of Cyclotrons in Selected Facilities of Karachi

Facility	Cyclotron	Energy MeV	Shield Category	Radionuclide Produced
A	ABT Cyclotron 1	7.5	Self-shielded	F-18
B	ABT Cyclotron 2	7.5	Self-shielded	F-18
C	Siemens Eclipse Cyclotron	11	Self-shielded	F-18
D	IBA Molecular Cyclone 18/9 Cyclotron	18	Un-shielded	F-18

(a)

(b)

(c)

Figure I: Types of Cyclotron; (a) ABT Cyclotron, (b) Siemens Eclipse Cyclotron, and (c) IBA Molecular Cyclone 18/9 Cyclotron

The facilities are designed and constructed in accordance with the kind of cyclotron that will be installed. For instance, Siemens Eclipse and IBA Molecular Cyclone 18/9 cyclotrons have a maze structure in the bunker of the cyclotron and a separate Hot Cell for radio-synthesis since un-shielded type cyclotrons need significant structural shielding. However, a maze-like structure is not necessary for a self-shielded cyclotron. Figure II, and figure III give an idea about the design of the facility for typical un-shielded and self-shielded cyclotrons respectively.

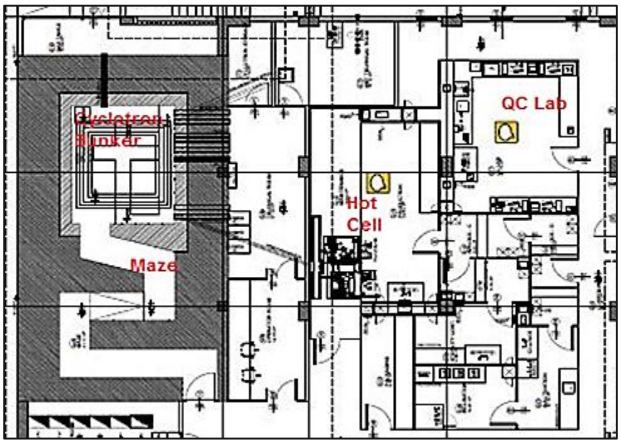


Figure II: Layout of IBA Molecular Cyclone 18/9 Cyclotron Area

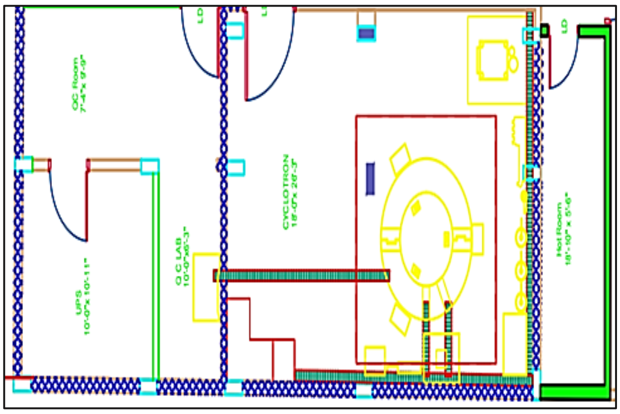


Figure III: Layout of Controlled Areas of ABT Cyclotron 1

The Cyclotron for isotope production and PET/CT scanning process involves a number of steps, from isotope production to radiopharmaceutical preparation and injection administration to patient PET/CT scanning, respectively. Cyclotron runs for 60 minutes on average; however, the daily run may differ from facility to facility based on the patient load listed in table II. As per typical procedure, the patient waits in the waiting area for roughly 40 to 50 minutes before being transferred for the PET scan. Typically, a PET/CT scan takes 20 to 40 minutes.

Table II: Run Time of Cyclotron

Facility	Cyclotron	Run Time	Per Week Run Routine	Activity Produced in One Run Time	No. of Patients Treated
A	ABT Cyclotron 1	60min	4	25mCi	15-20
B	ABT Cyclotron 2	60min	3-4	15-20mCi	12-15
C	Siemens Eclipse Cyclotron	60min	3	800-1200mCi	90-100
D	IBA Molecular Cyclone 18/9 Cyclotron	57min	3	3Ci	100-120

B. Thermoluminescent Dosimeter and Reader System

In this study, the two-chip TLD-100 (LiF: Mg, Ti) cards were used for measuring doses as shown in figure IV. The dose resulted due to exposure of gamma photons emitted from FDG received in the controlled areas and supervised of cyclotron-PET/CT facilities. TLD-100 is Lithium Fluoride (Li natural) crystal, which is doped with Magnesium and Titanium [11], and [12].

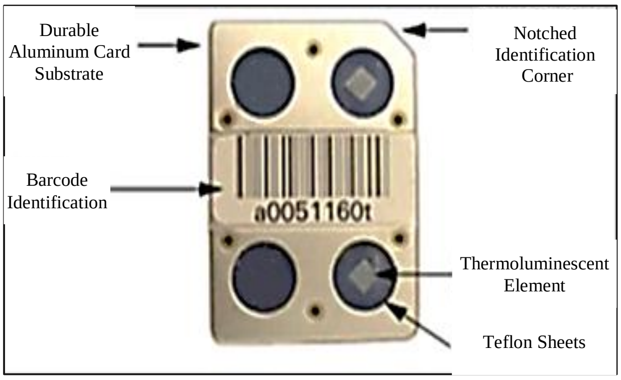


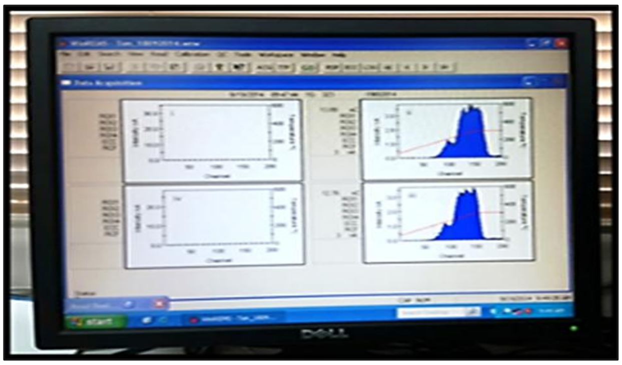
Figure IV: Schematic Diagram of Two Chip TLD-100 Card

For dose assessment, the exposed TLDs were processed in the TLD Reader system. An Automatic Harshaw 6600Plus TLD reader as shown in figure V; is used in the present study. The system consists of two major components: TLD Reader, and Windows Radiation Evaluation and Management System (WinREMS) software. The software controls the operation of the reader, including storing the operating parameters.

The following are major components of an Automatic Harshaw 6600Plus TLD reader [13]:

- **Heater:** It rises the temperature of the TLD crystal.
- **Photomultiplier Tube (PMT):** PMT amplifies and measures the stored light output of TLD crystal.
- **Meter/Recorder:** It displays results, and glow curves and records data of TLD.

(a)



(b)

Figure V: (a) Automated Harshaw 66ooPlus TLD Reader, and (b) Glow Curve

C. Radiation Level Monitoring at Workplace of Cyclotron-Pet/Ct Facilities

TLDs were annealed before being inserted. Ten (10) TLDs were installed for a period of 30 days in particular controlled and supervised areas of each of the four cyclotron-PET/CT facilities. The positions of TLDs are depicted in figure VI for Facility-A, where workplace radiation levels were monitored. The TLDs were positioned at the height of projected high exposure received by a worker (2m) and were chosen with consideration for the stay time of radiation workers, or occupancy factor.

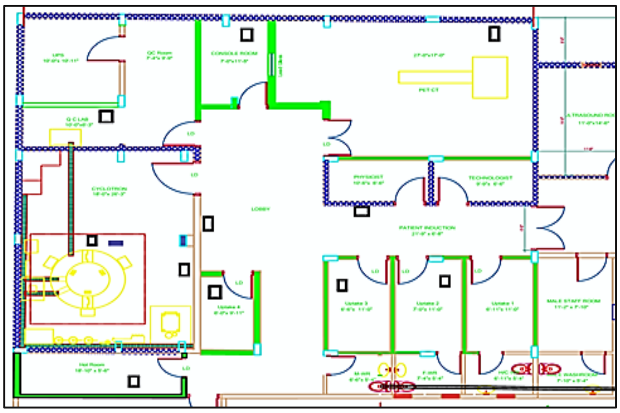


Figure VI: Map of Facility-A Cyclotron/PET Showing Locations of TLDs

After 30 days of exposure, the TLDs were collected back. These TLDs were processed for dose evaluation on an Automatic Harshaw 6600Plus TLD reader.

The calculation of the annual radiation levels at the workplace from the results was made according to the following equation i.e., eq. (1) [6].

$$H\left(\frac{mSv}{yr}\right) = D_{TLD} * 12 * \frac{8}{24} \qquad (1)$$

Where:

H(mSv/year) is the annual radiation level at workplace,

$\mathbf{D_{TLD}}$ is the Dose received by TLD (mSv/month),

Factor 12 is for months/year,

Factor 8/24 is for working hours per day/monitoring hours per day, and,

T is the Area Occupancy factor, based on the mean stay time of a worker in that location (details given in table V) [14].

Note: *The factor 8/24 is the standard working hours of radiation workers at the workplace.*

D. Regulations on Radiation Protection, Pak/904

According to clause 26 of PAK/904; the licensee shall delineate and identify controlled and supervised areas by appropriate means, taking into account the nature and extent of radiation hazards in those areas. The areas selected for the current study according to the classification of area are listed in table III.

Table III: Details of Selected Locations

S. No.	Location	Classification of Area
1.	Cyclotron Vault	Controlled
2.	Outside Cyclotron Vault	Controlled
3.	PET/CT Console room	Controlled
4.	PET/CT room	Controlled
5.	Hot Lab	Controlled
6.	Hot Cell	Controlled
7.	QC Lab	Controlled
8.	Uptake Room 1	Controlled
9.	Uptake Room 2	Controlled
10.	Corridor	Supervised

IV. RESULTS AND DISCUSSION

As per PNRA Regulations on Radiation Protection PAK/904, the controlled area may satisfy the requirement of a dose greater than > 6mSv and for the supervised area greater than 1mSv in a year [4]. The measured radiation doses at the workplace of selected cyclotron-PET/CT facilities using TLDs are shown in table IV:

Table IV: Measured Radiation Levels (mSv/year) at Workplace using TLD

Facility	A	B	C	D
Location	**Dose mSv/yr (ABT Cyclotron-1)**	**Dose mSv/yr (ABT Cyclotron-2)**	**Dose mSv/yr (Siemens Eclipse Cyclotron)**	**Dose mSv/yr (IBA Cyclotron) Unshielded**
PET Console Room	1.584	2.076	1.13004	2.352
PET/CT Room	52.248	6.636	29.34	3444
Hot Lab	8.076	7.584	-	12.048
QC Lab	4.644	8.796	9.696	2.232
Uptake Room 1	6.78	3.984	12.564	6.096

Uptake Room 2	3.24	10.824	8.2392	6.228
Corridor	1.692	7.308	7.3476	1.968
Injection Room	4.236	-	1.872	-
Hot Cell	-	-	6.66	1.476
Cyclotron Vault	3.168	3.42	2.52	196836*
Outside Cyclotron Vault	8.352	0.377	-	-
Cyclotron Maze Vault	-	-	-	57820.8*
***Controlled area of the unshielded cyclotron**				

The comparison of the final results of the evaluated radiation levels at the workplace between facilities is presented in table V. The radiation levels of ten selected areas of the cyclotron PET/CT facility are comparable with dose criteria defined in clause 26 of PAK/904, which is also consistent with Requirement 24 of IAEA GSR Part 3 [15]. The radiation levels in the cyclotron vault and maze of the cyclotron vault of Facility-D are in the range of 1000mSv/yr) because of the unshielded type cyclotron.

Table V: Measured Radiation Levels (mSv/yr)

Radiation Levels (mSv/yr)						
Location	**Occupancy**	**Area**	**ABT Cyclotron -1**	**ABT Cyclotron -2**	**Siemens Eclipse Cyclotron**	**IBA Cyclotron 18/9 Cyclotron**
PET Console Room	1	Controlled	0.528	0.692	0.376	0.784
PET/CT Room	1/2	Controlled	8.708	1.106	4.89	0.574
Hot Lab	1	Controlled	2.692	2.528	3.232	4.016
QC Lab	1	Controlled	1.548	2.932	3.232	0.744
Uptake Room 1	1/2	Controlled	1.13	0.664	2.094	1.016
Uptake Room 2	1/2	Controlled	0.54	1.804	1.3732	1.038
Corridor	1/4	Supervised	0.0141	0.609	0.6123	0.164
Injection Room	1	Controlled	1.412	-	0.624	-
Hot Cell	1	Controlled	0	-	2.22	0.492
Cyclotron Vault	1/16	Controlled	0.066	0.07125	0.0525	4100.75 *
Outside Cyclotron Vault	1/2	Controlled	1.392	0.754	-	-
Cyclotron Maze Vault	1/16	Controlled	-	-	-	1204.6*

** Facility is not self-shielded and, therefore, is installed in a civil structure (shielding, maze) to ensure radiation protection. TLDs were mounted in this access control area to have an estimate of the dose in the un-shielded cyclotron vault during operation.*

The radiation levels at the workplace of self-shielded cyclotrons are graphically presented in figure VI. The variation in radiation levels between facilities is due to different structural designs and locations of rooms.

The comparison was made between Cyclotron areas of four facilities and graphically presented in figure VII. The injection room is separately available in Eclipse and ABT cyclotron 1. However, in the other two facilities, dispensing of injections is carried out in the uptake room.

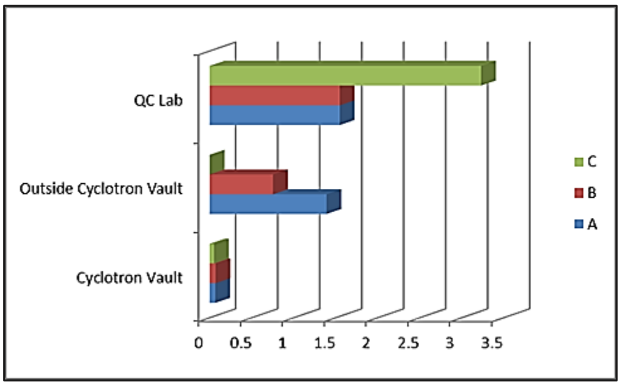


Figure VII: Comparison of Radiation Level (mSv/Yr) at Workplace in the Cyclotron Area

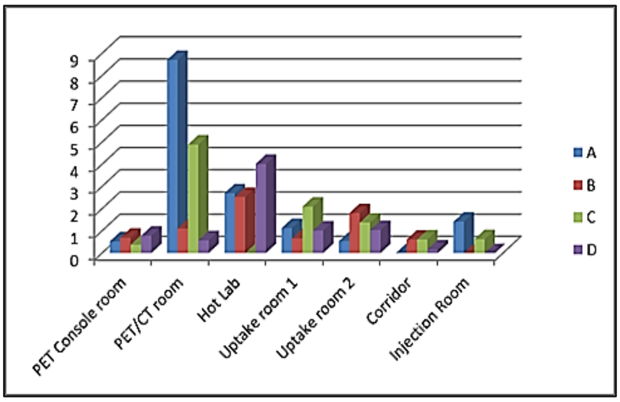


Figure VIII: Comparison of Radiation Level (mSv/Yr) at Workplace in the PET/CT Area

Figure VIII shows a comparison between the PET/CT areas of four institutions in graphic form. In addition, in the other two facilities, the dispensing of injections are done in the uptake room. The injection room is independently available in Eclipse and ABT cyclotron 1.

A comparative study was made with SANATANA et al., for the PET console room, PET/CT room, and corridor of PET facilities [6]. The detailed value of the dose rate is given in table VI, which are comparable, no significant deviation is observed.

Table VI: Comparison of Measured Radiation Levels with Study [10]

Location	Dose mSv/yr SANATANA et al. (2015)	Dose mSv/ yr (ABT Cyclotron-2)	Dose mSv/ yr (IBA Cyclotron) Unshielded
PET Console Room	0.48	0.692	0.784
PET/CT Room	1.08	1.106	0.574
Corridor	0.6	0.609	0.164

Researchers performed dose rate measurements with GM tube survey meters, which are active detectors. However, in the current study, TLDs were used, which are passive dosimeters. Graphically correlation between the dose rate measured by the GM Tube Survey meter and TLDs is shown in figure IX [8].

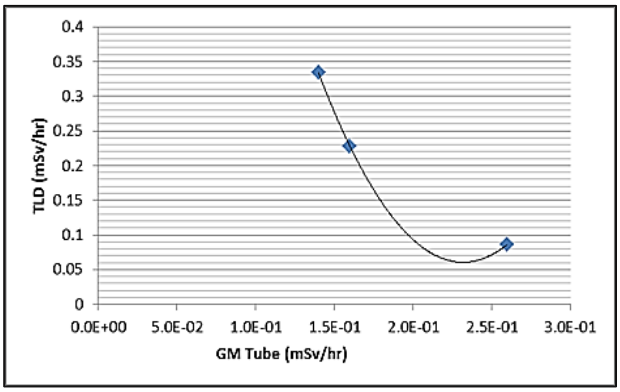


Figure IX: Comparison Correlation between the Dose Rate Measured by GM Tube Survey Meter, and TLDs [12]

The personal monitoring of radiation workers is performed using film badges and Optically Stimulated Luminescence (OSL). Figure X illustrates the comparison of radiation doses received by workers. The measured personal doses of radiation workers are much below the permissible dose limits (20mSv/yr) specified in PAK/904. M. Authors compared the doses received by workers involved in cyclotron operation and workers involved in the production of radiopharmaceuticals using GM tube detectors and neutron detectors [16]. The doses evaluated for cyclotron operators were well below the dose limits in comparison to workers in the production of radiopharmaceuticals. However, the radiation doses were within limits but these detectors overestimated the individual doses.

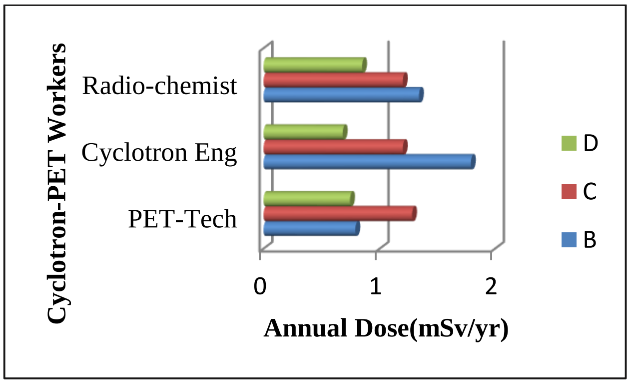


Figure X: Personal Doses of Radiation Workers

V. CONCLUSION

The results of the TLD evaluation show that the radiation levels at the workplaces of radiation workers at cyclotron-PET/CT facilities meet the criteria for area classification in the Radiation Protection Regulations (PAK/904), and they also meet Requirement 24 of the IAEA GSR Part 3. The measured radiation levels are well below the regulatory dose limits for the controlled area (>6mSv/yr) except in the unshielded cyclotron vault although it also meets the criteria and supervised area (>1mSv/yr).

The results obtained from TLDs are more reliable because of passive detectors. The results of the current study lead to the conclusion that the facilities have robust radiation safety protocols, such as facility shielding, personal dosimetry, ventilation arrangements, the availability of radiation detectors, etc., and an extensive radiation protection programme to reduce exposure to radiation for radiation workers and the general public. The workers at the facilities are knowledgeable about radiation protection and are adequately trained.

VI. FUTURE RECOMMENDATION

Future extensions of the study could include workplace and personal monitoring utilizing passive and active detectors with large data points for at least a minimum of one year each for verification of PAK/904.

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Authors Contributions

The authors confirm their contribution to the paper as follows: **Study Conception and Design:** Kauser Perveen, Syed Miskhat Ali, and Khalid Hussain; **Data Collection:** Kauser Perveen, and Hira Nadeem; **Analysis and Interpretation of Results:** Kauser Perveen, Ayesha Mohsin, and Syed Miskhat Ali; **Draft Manuscript Preparation:** Kauser Perveen, and Ayesha Mohsin.
All the authors reviewed the results and approved the final version of the manuscript.

Conflict of Interest

The author confirms that this work is original and not plagiarized from any other source, i.e., electronic or print media. The information obtained from all of the sources is properly recognized and cited below.

Data Availability Statement

The testing data is available in this paper.

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ABBREVIATIONS AND ACRONYMS

FDG: Fluorodeoxyglucose
PET/CT: Positron Emission Tomography / Computed Tomography
QA/QC: Quality Assurance/Quality Control
TLD: Thermoluminescene Dosimeter
WinREMS: Windows Radiation Evaluation and Management System