Radiation Physics and Chemistry 237 (2025) 112986

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Assessment of typical values for establishing institutional DRL of adult whole-body FLUORINE-18 Fluorodeoxyglucose (FDG) PET/CT scans in Malaysia cancer centre

H. Murat [a,b], M.M.A. Kechik [a], M.A. Said [c], S.I. Saufi [d], M.H.M. Zaid [a], M.K.A. Karim [a,e,*]

[a] Department of Physics, Faculty of Science, Universiti Putra Malaysia, Serdang, 43400 Selangor, Malaysia
[b] Department of Nuclear Medicine, Hospital Sultanah Aminah Johor Bahru, Johor, Malaysia
[c] Department of Nuclear Medicine, Institut Kanser Negara, Putrajaya, Malaysia
[d] Medical Radiation Surveillance Division, Ministry of Health Malaysia, Putrajaya, Malaysia
[e] Institute for Mathematical Research (INSPEM), Universiti Putra Malaysia, UPM Serdang, 43400, Selangor Malaysia

ARTICLE INFO

Handling Editor: Piotr Ulanski

Keywords:
Diagnostic reference level (DRL)
^{18}F-FDG
PET/CT
Effective dose
BMI

ABSTRACT

Since 1996, Diagnostic Reference Level (DRL) has been introduced as an essential benchmark for optimizing patient radiation protection in a medical setting. DRLs have been acknowledged and reported by several institutions even become part of authority to monitor the use of radiation in medical, including diagnostic nuclear medicine imaging. Hence, this study aimed to establish DRL typical values for adult whole-body Fluorine-18 Fluorodeoxyglucose (WB FDG) PET/CT scan and to compare these values with other references. We retrospectively analyzed 831 adult patients (mean weight, 69.08 ± 5.84 kg and BMI, 26.01 ± 3.19 kg/m^2) of their administered activity (A), administered activity concentration (C_A), volume weighted computed tomography dose index ($CTDI_{vol}$), dose length product (DLP) and effective dose ($E_{PET/CT}$). Descriptive statistical methods were used to determine the median as the typical values and assess their alignment with other reference levels. The results showed that the median A was 296.37 MBq, while the median C_A was 4.31 MBq/kg. For CT, the median $CTDI_{vol}$ was 7.77 mGy, and the median DLP was 818.34 mGy cm with the mean CT effective dose, E_{CT} contributing nearly 70 % of total $E_{PET/CT}$. Additionally, BMI was found to significantly affect radiation dose ($p < 0.05$) particularly in the CT, where dose increased with higher BMI. Our findings indicate that patient radiation protection for adult WB FDG PET/CT scans at our cancer center generally meet international standards. However, the observed dose variability suggests a need for further optimization to ensure more consistent application of DRL process.

1. Introduction

Over the last few decades, diagnostic medical imaging has become one of the most common sources of artificial ionizing radiation globally. This demand is driven by the need for non-invasive diagnostic tools that help clinicians address a wide variety of clinical issues. Therefore, hybrid imaging technology, such as Positron Emission Tomography (PET) combined with computed tomography (CT) namely PET/CT has been developed (Townsend and Thomas, 2002). This combined technology allows patients to undergo both scans in one sitting, producing more detailed functional and anatomical information. It is particularly useful for diagnosing and monitoring cancers, radiotherapy planning, inflammatory diseases, heart conditions, and neurological disorders (Jarritt et al., 2006; Murat et al., 2024; Régis et al., 2023). However, the scan requires both internal radiation exposure from radiopharmaceuticals in PET and external radiation exposure from CT, leading to a growing interest from the professionals in monitoring and optimizing the ionizing radiation involved (Murat et al., 2023; Salah et al., 2020).

To maximize the benefits from the use of ionizing radiation, the International Commission for Radiological Protection (ICRP) introduced the DRL guidelines since 1996 (ICRP, 2017). These guidelines encourage professionals from the regulatory bodies, and medical institutions to set safety benchmarks for radiation exposure that align with theranostic objectives. DRL serves as a good practice tool to reduce radiation exposure while maintaining diagnostic performance. The values are determined from the 75th percentile of the DRL typical value

* Corresponding author. Department of Physics, Faculty of Science, Universiti Putra Malaysia, Serdang, 43400 Selangor, Malaysia.
E-mail address: mkhalis@upm.edu.my (M.K.A. Karim).

https://doi.org/10.1016/j.radphyschem.2025.112986
Received 8 November 2024; Received in revised form 28 April 2025; Accepted 26 May 2025
Available online 28 May 2025

distribution of the selected patient dose parameter from multiple facilities in a retrospective survey (Karim et al., 2016). Recent studies recommend the median data distribution of A, C_A, $CTDI_{vol}$, and DLP as reliable parameters for DRL typical value in PET/CT, while $E_{PET/CT}$ serves as an indicator for assessing the associated risks of radiation exposure (Poli et al., 2020; Wachabauer et al., 2022). In addition to these parameters, BMI and patient gender should be included in evaluating patient radiation risk in PET/CT (Brix et al., 2014; Karim et al., 2017).

In Malaysia, national DRL (NDRL) have not been specified in the literature, but the local guidelines were based on the mean typical value from a national survey following the previous ICRP recommendation (MOH Malaysia, 2013b). In contrast, country like Japan have made significant progress by revising the national DRLs for PET/CT to include body weight-based adminstered activity optimization, which has been shown to reduce radiation dose by 11 % and improve image quality by 10 % (Abe et al., 2020). A study conducted in Kuwait, have highlighted the importance of establishing NDRL for the CT component in PET/CT scan (Masoomi et al., 2021). The study found a 9.1 % improvement in DRLs compared to the previous study, indicating the need for ongoing monitoring (Masoomi et al., 2019). Similarly, in Thailand, NDRL for nuclear medicine were established by surveying administered activities of radiopharmaceuticals across 21 medical facilities covering 4641 SEPCT or SPECT/CT procedures and 409 PET procedures. However, the Thailand NDRLs for FDG PET were higher than in some countries but lower than in others, such as the United States and the European Union (Suttho, 2024).

It can be concluded that DRL is essential tools in PET/CT scan for optimizing patient radiation dose through systematic dose survey. However, over time as medical practice change or technology change, it has become evident that an updated survey and publicly access the typical values is necessary for the effective implementation of the DRL process in clinical settings. Therefore, the study aims to report the DRL typical value for adult WB FDG PET/CT scans in a Malaysia cancer center with specific attention to the impact of BMI, and to compare the value with established DRLs for future optimization. The study will provide updated data for the implementation of the DRL process in clinical practice.

2. Materials and methods

2.1. Study design

This retrospective study was conducted at the largest cancer center in Malaysia, following approval from the Medical Research and Ethics Committee (MREC) of the Ministry of Health Malaysia (MOH) under the identification number NMRR ID-24-00362-FSE. Informed consent was waived due to the retrospective nature of the data, and all data collection adhered to institutional ethical guidelines. Assessment was performed using the PET/CT Discovery MI system from GE Healthcare, USA (Fig. 1a). This system utilizes lutetium-yttrium oxyorthosilicate (LYSO) crystal scintillators paired with photomultiplier tube (PMT) detector to provide high-resolution PET scan with time-of-flight (TOF) technology for enhanced precision. The CT component of the system features 64-row detectors that are capable of reconstructing 128 slice images per gantry rotation. It incorporates adaptive statistical iterative reconstruction (ASiR) technology to minimize radiation exposure.

Data was collected from 831 adult patients, consisting of 428 men and 403 women who underwent WB FDG PET/CT scan. The data for each patient included patient age, gender, height, weight, A in Mega-Baquaeral (MBq), $CTDI_{vol}$ in miliGray (mGy), and DLP in miliGray. centimeter (mGy.cm).

2.2. PET/CT imaging protocols

The positron emitter radioisotope, fluorine-18 (^{18}F) was generated in-house at the nearby cyclotron facility and then labelled with glucose analogue, FDG for radiopharmaceutical administration. Prior to administration, patients were advised to fast for 6 h. The FDG was then administered intravenously by credentialed technologist. The average amount of A for a WB protocol was 305.79 MBq with a range from 160.95 MBq to 1176.6 MBq following a linear weight-based dosing protocol. The scanning procedure were performed 1 h post-radiopharmaceutical administration to allow for optimal uptake time. The average duration of each procedure was approximately 30 min, with image acquisition performed for 2 min per bed position covering the area from the skull vertex to the mid-thigh. Post-processing procedures utilized TOF reconstruction technology along with advanced iterative reconstruction algorithm.

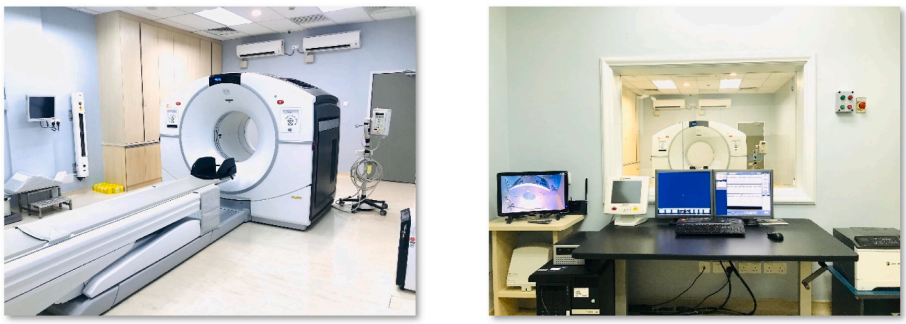
For the CT component, the image acquisition was performed at low-dose mode with exposure parameter set at constant tube voltage of 120 kVp and variable tube current (mA) using the automatic tube current modulation (ATCM) technology. Iterative reconstruction algorithm known as ASiR was applied to further reduce radiation dose tailored to patient characteristics such as body size and clinical indication.

2.3. Assessment of DRL quantity

DRL quantity is a specific radiation dose parameter that measures the quantity of ionizing radiation required to execute a diagnostic imaging procedure. According to ICRP Publication 135, DRL quantities should be easy to measure such as A, and C_A for PET component, $CTDI_{vol}$ and DLP for CT component (ICRP, 2017). Therefore, we calculated the C_A for PET component based on Equation (1).

$$C_A = \frac{A}{m} \tag{1}$$

where A is the amount of FDG injected into the patient's body in MBq,



(a) (b)

Fig. 1. PET/CT GE Discovery MI Scanner (a), and control console (b) used in this study.

and m is the patient body weight in kg.

For CT component, we collected two types of DRL quantities namely $CTDI_{vol}$ and DLP from the scanner control console for every patient. $CTDI_{vol}$ is the standard parameter used to estimate the scanner output relative to patient dose for a specific protocol. It represents the dose averaged over the scan volume for multi-slice scanning following Equation (2).

$$CTDI_{vol} = \frac{CTDI_W}{pitch} \tag{2}$$

where $CTDI_w$ is the weighted $CTDI$, which accounts for the dose measured at the center and periphery of a single slice of a $CTDI$ phantom using a 100 mm pencil-type ionization chamber, and pitch is the ratio of the table movement per rotation to the x-ray beam width.

Additionally, DLP is an estimate of the amount of radiation exposure during the entire CT procedure presented as shown in Equation (3).

$$DLP = CTDI_{vol} \times L \tag{3}$$

where $CTDI_{vol}$ is the estimated dose over the scan volume in mGy, and L is the scan length in cm.

To investigate the relationship between BMI with DRL quantities, we categorized patients into three BMI groups namely normal weight (18.5–24.9 kg/m^2), overweight (25–29.9 kg/m^2), and obese (>30 kg/m^2). DRL quantities were compared across these groups, with separate analyses for male and female patients.

2.4. Assessment of effective dose

This study estimates the effective dose for both the PET and CT components of PET/CT scans and analyzes the correlation with patient weight and BMI. The effective dose for the PET component was calculated using Equation (4).

$$E_{PET} = A \times k \tag{4}$$

where A is the administered activity (MBq), and k is the dose coefficient (0.019 mSv/MBq) provided by ICRP Publication 106 (ICRP, 2008).

Moreover, the effective dose for CT component was estimated using conversion factors specific to the scanning body region as shown in Equation (5).

$$E_{CT} = DLP \times CF \tag{5}$$

where DLP is the dose length product (mGy.cm), and CF is the conversion factor for whole-body scans (0.015 mSv/mGy.cm) provided by ICRP Publication 102 (ICRP, 2007). Then, we calculated the total effective dose, $E_{PET/CT}$ by adding the E_{PET} and E_{CT}.

2.5. Comparison of typical value with established DRLs

Following the updated guideline from ICRP, we calculated the typical value for each DRL quantity in adult WB FDG PET/CT scans for further comparison (ICRP, 2017). These typical value including A, C_A, $CTDI_{vol}$ and DLP were then systematically compared to determine if they exceed or fall below the published DRLs. We compared with the local and recently published international DRLs over a period of 6 years from 2019 to 2024.

2.6. Statistical analysis

Statistical analysis was conducted using Microsoft Excel for Microsoft 365 MSO, version 2409 (Microsoft Corporation, Redmond, WA, USA) and OriginPro, version 2024 (OriginLab Corporation, Northampton, MA, USA) on data collected from WB FDG PET/CT scans across the cancer center. The analysis focused on A, C_A, $CTDI_{vol}$, DLP and $E_{PET/CT}$. For each quantity, the number of entries, mean, standard deviation, minimum and maximum values, as well as the 25th, 50th (median) and 75th percentiles, were calculated and presented in either a table, scatter plot, box chart, or histogram. The median values of DRL quantity were then used to report as the typical value for further optimization.

3. Results and discussion

3.1. Patient demographics

Table 1 provides a summary of the patient age, weight, height, and BMI based on gender of the patients. A notable observation is the difference in BMI between males and females, with females have a higher mean BMI (27.44 ± 3.10) than males (24.67 ± 2.64). This difference in patient demographics may have implications for administered activity and radiation exposure during the PET/CT scans to achieve a balance with image quality. Image quality in PET/CT scans is significantly affected by the relatively increased size of the patient due to increased photon attenuation and scattering (Inoue, 2022; Xiao et al., 2021).

This study has evaluated radiation dose associated with DRL quantities from the WB FDG PET/CT scans. The analysis was conducted separately for the PET component and CT components, followed by estimation of the $E_{PET/CT}$. The histogram in Fig. 2 presents the distribution of A and C_A for the PET component with minimal skewness. The median A and C_A were found to be 295.63 MBq and 4.31 MBq/kg respectively, which will consider as typical value for further DRL assessment. The mean A and C_A were slightly higher at 303.23 MBq and 4.43 MBq/kg respectively. The 25th percentile (266.03 MBq) and the 75th percentile (331.89 Mbq) provide valuable reference points for local dose optimization efforts.

As seen in Fig. 3, boxplots illustrate the A and C_A increase with higher BMI categories for both male and female patient. However, in the obese category (BMI >30 kg/m^2), a higher variability in doses is observed especially among female patient, where some values exceed 500 MBq. These findings indicate that A in obese patients often exceed the typical values established by this study. While it is common practice to increase the dose for patient with higher BMI, the significant variability suggests the need for more tailored guidelines to ensure that doses remain within safe and optimized ranges to ensure radiation risk for this group.

3.2. DRL quantity from the CT component

In addition to the PET component, Fig. 4 presents the distribution of $CTDI_{vol}$ and DLP for the CT component, which both critical in determining the DRL for PET/CT scans. The median $CTDI_{vol}$ was 7.77 mGy, with a mean of 8.09 mGy, and the interquartile range (IQR) is from 6.45 mGy to 9.34 mGy. This suggests that consistent delivery dose in the majority of cases. Similarly, the median DLP was 818.34 mGy cm, with a mean of 843.63 mGy cm, and an IQR from 672.77 mGy cm to 985.15 mGy cm. The relatively narrow spread of both parameters indicates that the CT component doses are generally consistent dose management across most cases. However, attention should be paid to the few outliers, as these could represent examinations where doses exceeded the recommended DRL values.

Boxplots in Fig. 5 further present $CTDI_{vol}$ and DLP distributions by BMI categories and gender, revealing significant findings for the CT optimization consistent with DRL recommendations. The median $CTDI_{vol}$ increases with BMI, which is expected as higher body mass requires more radiation to penetrate tissues. For patient with normal BMI (18.5–24.9 kg/m^2), the median $CTDI_{vol}$ for both males and females were around 7 mGy, which within the acceptable DRL range. However, for the obese patients (BMI ≥30 kg/m^2), the median $CTDI_{vol}$ increases to around 10 mGy, with females receiving slightly higher doses than males. A similar trend was observed for DLP, where values increased with BMI, particularly in the obese patients, where median DLP values approach

Table 1
Patient demographics for WB FDG PET/CT scans by gender.

Characteristics	Male (n = 428)		Female (n = 403)		Total (n = 831)
	Range (Min-max)	Mean ± SD	Range (Min-max)	Mean ± SD	Mean ± SD
Age (year)	19–88	56.12 ± 17.05	20.00–87.00	54.02 ± 15.00	55.11 ± 16.12
Weight (kg)	60.08–80.50	68.26 ± 5.86	60.00–80.80	69.95 ± 5.70	69.08 ± 5.84
Height (cm)	139.00–184.00	163.47 ± 7.84	139.00–182.00	160.09 ± 7.91	163.47 ± 7.84
BMI (kg.m^{-2})	18.94–34.75	24.67 ± 2.64	19.93–36.89	27.44 ± 3.10	26.01 ± 3.19

DRL quantity from FDG PET Component.

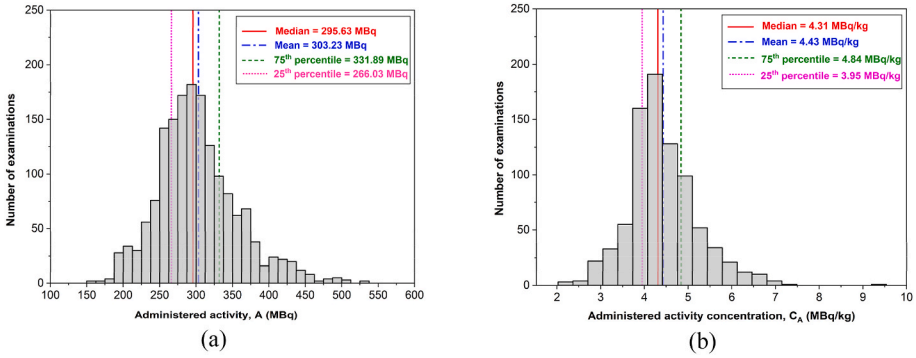


Fig. 2. Distribution of (a) administered activity, A and (b) administered activity concentration, C_A for the radiopharmaceutical in the PET component.

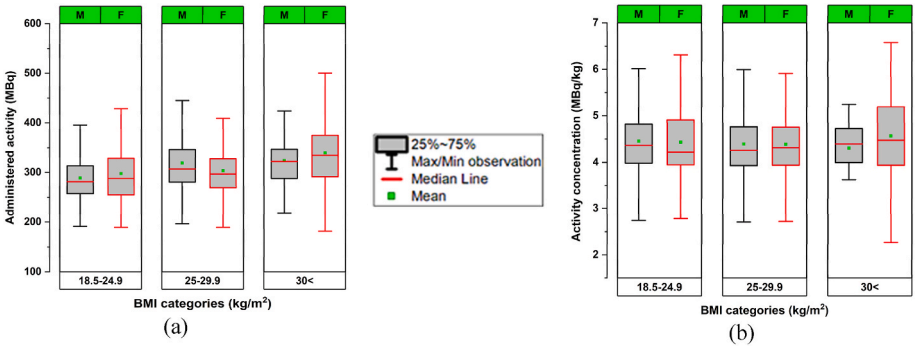


Fig. 3. Comparison of A (a), C_A (b) with different gender (M = Male, F=Female) and BMI categories for the radiopharmaceutical in the PET component.

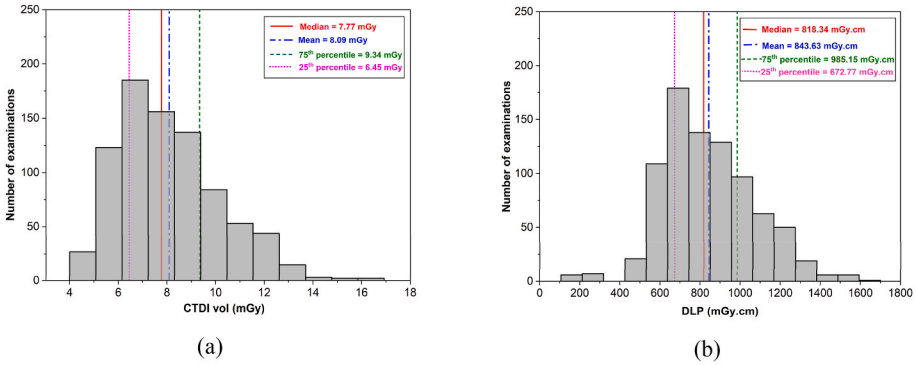


Fig. 4. Distribution of $CTDI_{vol}$ (a), and DLP (b) for the CT component.

1200 mGy cm. This variation in dose among obese patients is likely due to the ATCM technology which compensates for increased tissue density by elevating the tube current and results in increasing radiation output. However, several parameters such as scan length and tube voltage can also be manually adjusted to improve dose optimization. These findings highlight the need for more stringent dose control, especially for females, who consistently received higher doses than males.

The notable limitation of the study is the variability in radiation dose for the CT component, particularly in the DLP values, which show a wide range. This variability suggests the lack of standardization across CT protocols, leading to inconsistent radiation exposure. Overexposure may increased the long-term radiation risk while underexposure may

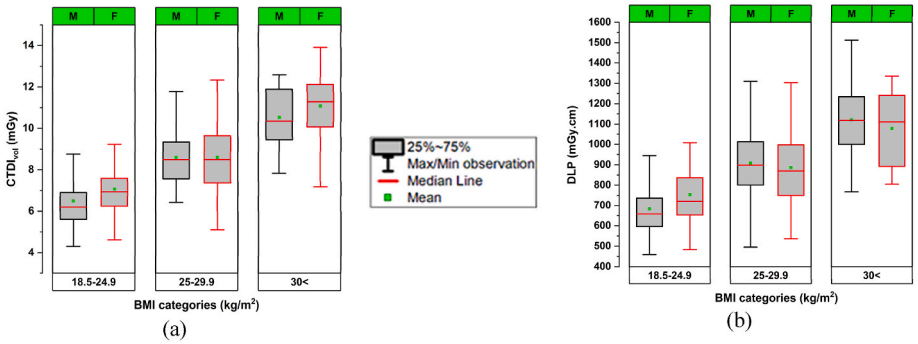


Fig. 5. Comparison of $CTDI_{vol}$ (a), and DLP (b) with different gender (M = Male, F=Female) and BMI categories for the CT component.

compromise diagnostic accuracy. This lack of protocol standardization may limit the optimization of the DRL process especially for the CT component in clinical setting. Addressing this issues requires implementation of advanced imaging technologies such as reconstruction algorithm and real-time dose monitoring system. Therefore, the approach from this study should be replicated for future study considering the factors that influence the CT dose in PET/CT scans.

3.3. Effective dose

The descriptive analysis of the effective dose from both the PET and CT components as summarized in Table 2, shows a clear disparity in their contributions to the total dose. The CT component contributed for nearly 70 % of the total effective dose, while the PET component contributed around 30 %. These findings align with previous studies, which also reported that the CT component typically contributes up to 80 % of the total radiation dose in adult FDG PET/CT scans (Adeleye and Chetty, 2018; Ben-Rejeb and Ben-Sellem, 2023; Xie et al., 2018). This difference in dose contribution was consistent across all weight and BMI categories, as illustrated in Fig. 6. Furthermore, the linear fit for the CT component shows a strong correlation between effective dose and both weight and BMI, indicating that CT dose increases with patient size. In contrast, the PET component showed weak correlations with these parameters, suggesting a more stable dose distribution across different body sizes.

The difference in effective doses between the PET and CT components can be explained by the fundamental roles of each modality in PET/CT imaging. The PET system is designed to provide functional imaging by detecting gamma rays emitted from the radiopharmaceutical, such as ^{18}F-FDG, which accumulates in metabolically active tissues. The radiation dose from PET primarily depends on the amount of administered radiopharmaceutical and its decay characteristics, which are standardized based on patient weight. As a result, the effective dose from PET remains relatively constant across patients of varying body sizes, as long as weight-based dosing protocols are followed.

On the other hand, the CT component is responsible for providing detailed anatomical images and plays a crucial role in attenuation correction during PET/CT scans. Unlike PET, the CT system uses X-rays which must penetrate the body to create cross-sectional images. The amount of radiation required increases with the thickness and density of the tissues, which are correlated with patient weight and BMI. As patient size increases, more radiation is needed to maintain image quality, leading to a higher CT dose (Harun et al., 2021). Consequently, the overall effective dose from the CT component rises in larger patients, as demonstrated by the strong correlation between CT dose and both weight and BMI.

Table 2
Descriptive analysis of effective dose by PET and CT component.

Descriptive parameter	E_{PET} (mSv)	E_{CT} (mSv)	Total $E_{PET/CT}$ (mSv)
Mean ± SD	5.81 ± 1.27	12.65 ± 3.45	18.46 ± 4.03
Q1 (25th percentile)	5.07	10.09	15.52
Q2 (50th percentile)	5.63	12.28	18.10
Q3 (75th percentile)	6.36	14.78	20.93

3.4. Local comparison

The comparison of DRL quantities between the current study, the Malaysian NDRL (MOH Malaysia, 2013a), and the LDRL (Ridhwan et al., 2023) indicates significant improvements in dose optimization for WB ^{18}F-FDG PET/CT scans as presented in Table 3. The median administered activity (296.37 MBq) in the current study is notably lower than the NDRL (433 MBq), but higher than the LDRL (212.35 MBq), suggesting that is potential for further dose optimization. Additionally, the median $CTDI_{vol}$ (7.77 mGy) and *DLP* (818.34 mGy cm) are significantly lower than the LDRL values, reflecting advancements in CT dose management through optimized protocols (see Table 4).

Their improvement in radiation dose align with the ALARA (As Low As Reasonably Achievable) concept which seeks to minimize radiation exposure while maintaining diagnostic performance (Murat et al., 2023; Towson and Eberl, 2006). The lower administered activity observed compared to the Malaysian NDRL can be attributed to advancements in PET technology. In particular, innovations such as time-of-flight (TOF) and improvements in detector sensitivity have allowed for better image quality with lower administered activity (Murat et al., 2024). The significant reduction in $CTDI_{vol}$ and *DLP* compared to the LDRL, are likely due to advancements in CT technology and optimization of scanning protocols (Karim MKA et al., 2016). Innovations such as iterative reconstruction algorithms and automated exposure control (AEC) systems have played a key role in lowering radiation doses without compromising image quality (Inoue, 2022). Previous studies have consistently shown that optimizing CT parameters with dose-reduction technologies, including adaptive dose modulation can significantly decrease overall radiation exposure (Al-Othman et al., 2022; Choopani et al., 2022).

A limitation of this local comparison is the limited availability of published DRL value, particularly for PET/CT. Although this study has taken the initiative to compare its dose data with the available local DRL values, the shortage of comprehensive and up-to-date published DRL values makes it challenging to assess the typical value for WB ^{18}F-FDG PET/CT scans. For instance, the comparison of C_A (MBq/kg) is limited due to the absence of corresponding data from both NDRL and LDRL sources. This lack of data is likely due to the focused on *A* rather than normalizing doses to patient body weight. Furthermore, the limited availability of CT dose parameters, such as $CTDI_{vol}$ and *DLP* in local guidelines complicates the optimization process. Therefore, without a comprehensive DRL value, it is difficult to fully assess the typical value and further optimize radiation exposure in PET/CT. Updating the local DRL would assist in refining optimization strategies by implementing the DRL process more effectively in the future.

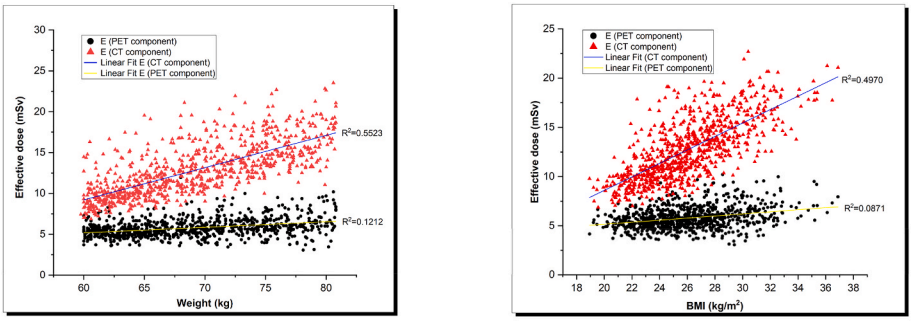


Fig. 6. Relationship between effective dose, weight (a), and BMI (b) for PET and CT components in whole body PET/CT scans.

Table 3
Comparison of DRL quantities between current study, LDRL and Malaysian NDRL for WB FDG PET/CT scans.

DRL Quantity	Data in this study (2023)		NDRL Malaysia (MOH Malaysia, 2013a) (Q3)	LDRL Malaysia, (Ridhwan et al., 2023) (Q3)
	Median	Q3		
A (MBq)	296.37	334.48	433	212.35
C_A (MBq/kg)	4.31	4.84	–	–
$CTDI_{vol}$ (mGy)	7.77	9.34	–	12.48
DLP (mGy.cm)	818.34	985.15	–	1198

Q3 = 3rd quartile, NDRL = National DRL and LDRL = Local DRL.

3.5. International comparison

DRLs vary by country due to differences in imaging technology, clinical protocols, and patient populations, as evidenced by the wide range of DRL values reported in the literature. Typically, DRL values were established based on 75th percentile of dose distributions from a large number of facilities (ICRP, 2017). Table 3 shows the comparison between the current study's median typical value for WB FDG PET/CT scans and published international DRLs from 2019 to 2024. The administered activity A in this study (296.37 MBq) falls within an acceptable range compared to most international values. In terms of C_A, the current study (4.31 MBq/kg) aligns with Saudi Arabia (4.41 MBq/kg) and Jordan (3.70 MBq/kg), but it is lower than China (5.22 MBq/kg). Similarly, the $CTDI_{vol}$ in the current study (7.77 mGy) is notably lower than Saudi Arabia (11.00 mGy) and Jordan (10.10 mGy). Additionally, the DLP (818 mGy.cm) in this study is lower than Saudi Arabia (1160 mGy.cm) and Jordan (1118 mGy.cm). These findings reflect the modern PET/CT technologies such as, TOF, and advanced iterative reconstruction algorithms which allow for lower A while maintaining image quality (Gundacker and Heering, 2020; Schaart, 2021). Additionally, dose modulation techniques in CT, such as AEC further optimizes radiation exposure (Inoue, 2022; Karim et al., 2016). However, variations in A may also be influenced by differences in patient characteristics, such as BMI (Xiao et al., 2021).

The results also reveal differences in DRL values across countries, with several not reporting data for C_A and $CTDI_{vol}$. This discrepancy likely arises from variations in clinical protocols, influenced by local practices and technologies available. Inconsistent data definitions and lack of specific coding across countries further complicate DRL standardization (Alhorani et al., 2023b; Kabeer et al., 2024). The survey of worldwide PET facilities showed that not all centers had access to the same level of technology which directly impact DRL settings (Beyer et al., 2011). Furthermore, environmental factors including the location of the hospital may contribute to variations in DRLs as urban hospitals may have different procedural intensities compared to rural hospitals.

This study focused on establishing typical values and comparing them with local and international DRLs but did not include the crucial step of optimization which is essential for completing the DRL process. The exclusion of the optimization phase was primarily due to time constraints, as validating optimized imaging protocols across a broad range of patient populations requires extensive follow-up, which was beyond the scope of this study. Another limitation is that the study relied on data from a single facility, which restricts its ability to capture a broader range of clinical practices, patient demographics, and imaging protocols. For future studies, a more comprehensive approach involving multiple facilities and incorporating the optimization process will be necessary to improve radiation protection and further enhance utilization of DRL.

Table 4
Comparison of DRL quantities between current study, international published DRL for WB ^{18}F-FDG PET/CT scans.

DRL Quantity	Current study (Typical value)	NDRL KW (Masoomi et al., 2021)	NDRL KSA (Alkhybari et al., 2022)	NDRL JOR (Alhorani et al., 2023a)	NDRL JPN (Abe et al., 2020)	NDRL CHN (Wang et al., 2023)	NDRL AUS (Alkhybari et al., 2019)	NDRL NZL (Alkhybari et al., 2019)	NDRL AUT (Wachabauer et al., 2022)	LDRL GRC (Tzampazidou et al., 2021)	NDRL USA (Becker et al., 2019)
A (MBq)	296.37	–	307.10	303.00	240	–	333.75	332.87	300.00	361.60	555
C_A (MBq/kg)	4.31	–	4.41	3.70	4.00	5.22	–	–	4.00	–	–
$CTDI_{vol}$ (mGy)	7.77	4.10	11.00	10.10	6.10	–	–	–	–	4.80	–
DLP (mGy.cm)	818	684	1160	1118	600	922	–	–	–	426	–

KW = Kuwait, KSA = Kingdom of Saudi Arabia, JOR = Jordan, JPN = Japan, CHN = China, AUS = Australia, NZL = New Zealand, AUT = Austria, GRC = Greece, USA = United States of America, NDRL = National DRL and LDRL = Local DRL.

4. Conclusion

This study successfully reported the DRL typical values for WB FDG PET/CT scans, comparing them with with both local and international DRLs, and assessing their contribution to the effective dose. The findings reveal that the CT component contributed nearly 70 % of the total effective dose, while the PET component contributed around 30 %. This emphasizes the for-dose optimization primarily in the CT component for patients with higher BMI where radiation exposure tends to be higher. The median administered activity in this study was lower than the Malaysian NDRL but higher than the established LDRL, suggesting opportunities for further reductions in PET dose. Additionally, the median $CTDI_{vol}$ and *DLP* were also significantly lower than the LDRL values, indicating well-optimized protocols in CT. In comparison to international DRLs, the typical values in this study are in line with most global standards, highlighting the effectiveness of current practices. Despite the positive findings, this study was limited by the absence of the optimization process and reliance on data from a single facility. Future studies should involve multiple facilities to capture a wider range of PET/CT procedures and patient demographics. Moreover, incorporating optimization steps would enhance radiation protection, and improve the overall utilization of DRLs in PET/CT scans.

CRediT authorship contribution statement

H. Murat: Writing – original draft, Methodology, Investigation, Formal analysis. **M.M.A. Kechik:** Validation, Resources, Project administration. **M.A. Said:** Resources, Methodology. **S.I. Saufi:** Visualization, Data curation. **M.H.M. Zaid:** Validation, Software. **M.K.A. Karim:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The Author(s) declare(s) that there is no conflict of interest.

Acknowledgement

This research was funded by Universiti Putra Malaysia under Geran Putra Inisiatif (GP/GPI 9762000).

Data availability

Data will be made available on request.

References

Abe, K., Hosono, M., Igarashi, T., Iimori, T., Ishiguro, M., Ito, T., Nagahata, T., Tsushima, H., Watanabe, H., 2020. The 2020 national diagnostic reference levels for nuclear medicine in Japan. Ann. Nucl. Med. 34, 799–806. https://doi.org/10.1007/s12149-020-01512-4.

Adeleye, B., Chetty, N., 2018. Radiation dose from 18F-FDG PET/CT procedures: influence of specific CT model and protocols. Radioprotection (Paris, 1966) 53, 107–113. https://doi.org/10.1051/radiopro/2018009.

Alhorani, Q., Alkhybari, E., Rawashdeh, M., Latiff, R.A., Sabarudin, A., Al-Ibraheem, A., Mohamad, M., 2023a. National and local diagnostic reference levels for 18F-FDG and CT in Jordanian PET/CT scanning: findings and implications in practice. https://doi.org/10.21203/rs.3.rs-3049856/v1.

Alhorani, Q., Alkhybari, E., Rawashdeh, M., Sabarudin, A., Latiff, R.A., Al-Ibraheem, A., Vinjamuri, S., Mohamad, M., 2023b. Revising and exploring the variations in methodologies for establishing the diagnostic reference levels for paediatric PET/CT imaging. Nucl. Med. Commun. 44, 937–943. https://doi.org/10.1097/MNM.0000000000001748.

Alkhybari, E.M., Alhulail, A.A., Sulieman, A., Faqeeh, J.M., Albatly, A.A., Alqarni, A.O., 2022. Deriving local diagnostic reference levels for four common adult PET/CT procedures in a Saudi Arabian hospital. J Radiat Res Appl Sci 15, 380–385. https://doi.org/10.1016/j.jrras.2022.08.011.

Alkhybari, E.M., McEntee, M.F., Brennan, P.C., Willowson, K.P., Kench, P.L., 2019. Diagnostic reference levels for 18F-FDG whole body PET/CT procedures: results from a survey of 12 centres in Australia and New Zealand. J Med Imaging Radiat Oncol 63, 291–299. https://doi.org/10.1111/1754-9485.12857.

Al-Othman, A.Y., Al-Sharydah, A.M., Abuelhia, E.I., Mohtasib, R., Bin Dahmash, A., Hegazi, T.M., Tajaldeen, A.A., Alshehri, S.S., Al-Malki, F.M., Alghamdi, S., 2022. Radiation dose optimization based on Saudi national diagnostic reference levels and effective dose calculation for computed tomography imaging: a unicentral cohort study. Applied Sciences 12, 11504. https://doi.org/10.3390/app122211504.

Becker, M.D., Butler, P.F., Siam, M., Gress, D.A., Ghesani, M., Harkness, B.A., Yoo, D.C., Oates, M.E., 2019. U.S. PET/CT and gamma camera diagnostic reference levels and achievable administered activities for noncardiac nuclear medicine studies. Radiology 293, 203–211. https://doi.org/10.1148/radiol.2019190623.

Ben-Rejeb, N., Ben-Sellem, D., 2023. Evaluation of radiation doses of the 18FDG PET/CT hybrid imaging in adult and paediatric oncologic patients. Radiat. Phys. Chem. 203, 110637. https://doi.org/10.1016/j.radphyschem.2022.110637.

Beyer, T., Czernin, J., Freudenberg, L.S., 2011. Variations in clinical PET/CT operations: results of an international survey of active PET/CT users. J. Nucl. Med. 52, 303–310. https://doi.org/10.2967/jnumed.110.079624.

Brix, G., Noßke, D., Leche, U., 2014. Radiation exposure of patients undergoing whole-body FDG-PET/CT examinations. Nuklearmedizin 53, 217–220. https://doi.org/10.3413/Nukmed-0663-14-04.

Choopani, M.R., Abedi, I., Dalvand, F., 2022. Pragmatic approaches to reducing radiation dose in brain computed tomography scan using scan parameter modification. J Med Signals Sens 12, 219–226. https://doi.org/10.4103/jmss.JMSS_83_20.

Gundacker, S., Heering, A., 2020. The silicon photomultiplier: fundamentals and applications of a modern solid-state photon detector. Phys. Med. Biol. 65, 17TR01. https://doi.org/10.1088/1361-6560/ab7b2d.

Harun, H.H., Abdul Karim, M.K., Muhammad, N.A., Awang Kechik, M.M., Chew, M.T., Talib, Z.A., 2021. Task-based assessment on various optimization protocols of computed tomography Pulmonary Angiography examination. Radiat. Phys. Chem. 188. https://doi.org/10.1016/j.radphyschem.2021.109692.

ICRP, 2017. Diagnostic reference levels in medical imaging. ICRP publication 135. Ann. ICRP 46 (1). https://doi.org/10.1177/0146645317717209. Ann. ICRP.

ICRP, 2008. Radiation dose to patients from radiopharmaceuticals - addendum 3 to ICRP publication 53. ICRP publication 106. Ann. ICRP 38 (1–2). ICRP Publication 106.

ICRP, 2007. Managing patient dose in multi-detector computed tomography (MDCT). ICRP publication 102. Ann. ICRP 37 (1).

Inoue, Y., 2022. Radiation dose modulation of computed tomography component in positron emission tomography/computed tomography. Semin. Nucl. Med. 52, 157–166. https://doi.org/10.1053/j.semnuclmed.2021.11.009.

Jarritt, P., Carson, K., Hounsell, A., Visvikis, D., 2006. The role of PET/CT scanning in radiotherapy planning. Br. J. Radiol. 79, 27–35. https://doi.org/10.1259/bjr/35628509.

Kabeer, S., Aliyu, S., Umar, F., Kamal, I., Muhammad, N.A, Karim, M.K.A., 2024. Establishment of diagnostic reference level for routine CT scan examination in sokoto state, Nigeria. Radioprotection 59, 197–202. https://doi.org/10.1051/radiopro/2024009.

Karim, M.K.A., Hashim, S., Bakar, K.A., Bradley, D.A., Ang, W.C., Bahrudin, N.A., Mhareb, M.H.A., 2017. Estimation of radiation cancer risk in CT-KUB. Radiat. Phys. Chem. 137, 130–134. https://doi.org/10.1016/j.radphyschem.2016.10.024.

Karim, M.K.A., Hashim, S., Bradley, D.A., Bakar, K.A., Haron, M.R., Kayun, Z., 2016. Radiation doses from computed tomography practice in Johor Bahru, Malaysia. Radiat. Phys. Chem. 121, 69–74. https://doi.org/10.1016/j.radphyschem.2015.12.020.

Karim, M.K.A., Hashim, S., Sabarudin, A., Bradley, D., Bahruddin, N., 2016. Evaluating organ dose and radiation risk of routine CT examinations in Johor Malaysia. Sains Malaysiana 45, 567–573.

Masoomi, M., Al-Shammeri, I., Al-Kandari, L., Elrahman, H., Al-Shammeri, J., 2021. National Diagnostic Reference Level (DRL) for nuclear medicine computed tomography–positron emission tomography hybrid imaging studies for Kuwait population: second phase dose audit-2019. BJR|Open 3, 20210020. https://doi.org/10.1259/bjro.20210020.

Masoomi, M., Al-Shammeri, I., Al-Shammari, J., Elrahman, H., Bashir, M., Bradley, D., 2019. Establishment of national DRL for CT in hybrid imaging studies “the first national NM CT (PET) dose audit for KW population.”. Int J Recent Sci Res 46, 835–836. https://doi.org/10.24327/ijrsr.2019.1007.3679.

MOH Malaysia, 2013a. Medical radiation exposure study in Malaysia. Medical Radiation Surveillance Division. Ministry of Health.

MOH Malaysia, 2013b. Malaysia diagnostic reference level (DRLs) in medical imaging (nuclear medicine). Medical Radiation Surveillance Division. Ministry of Health.

Murat, H., Awang Kechik, M.M., Chew, M.T., Kamal, I., Abdul Karim, M.K., 2024. Bibliometric review of optimization and image processing of positron emission tomography (PET) imaging system between 1981-2022. Curr Med Imaging Rev 20. https://doi.org/10.2174/0115734056282004240403042345.

Murat, H., Karim, M., Kechik, M., Amer, M., Razak, H., Kamal, I., Chew, M., 2023. Internal dose assessment of lymphoma 18 F-FDG Positron Emission Tomography (PET) scan. J Phys Conf Ser 2623, 012003. https://doi.org/10.1088/1742-6596/2623/1/012003.

Poli, G.L., Torres, L., Coca, M., Veselinovic, M., Lassmann, M., Delis, H., Fahey, F., 2020. Paediatric nuclear medicine practice: an international survey by the IAEA. Eur J Nucl Med Mol Imaging 47, 1552–1563. https://doi.org/10.1007/s00259-019-04624-w.

Régis, C., Benali, K., Rouzet, F., 2023. FDG PET/CT imaging of sarcoidosis. Semin. Nucl. Med. 53, 258–272.

Ridhwan, A.F.M, Chen, E.-J., Selvam, S.H.S., Chew, M.T., 2023. Analysis and establishment of adult diagnostic reference level for whole-body 18F-FDG PET/CT imaging: a single institutional study. Radiat. Phys. Chem. 210, 111022. https://doi.org/10.1016/j.radphyschem.2023.111022.

Salah, H., Mayhoub, F.H., Sulieman, A., Abuzaid, M., Al-Mohammed, H.I., Alkhorayef, M., Bradley, D.A., 2020. Fluoro-D-glucose (18F-FDG) PET/CT and patient effective dose. Radiat. Phys. Chem. 173, 108926. https://doi.org/10.1016/j.radphyschem.2020.108926.

Schaart, D.R., 2021. Physics and technology of time-of-flight PET detectors. Phys. Med. Biol. https://doi.org/10.1088/1361-6560/abee56.

Suttho, D., 2024. Establishment of national diagnostic reference levels for administered activity in diagnostic nuclear medicine in Thailand. J. Nucl. Med. Technol. 52, 158–162. https://doi.org/10.2967/jnmt.123.266836.

Townsend, David W., Thomas, Beyer, 2002. A combined PET/CT scanner: the path to true image fusion. Br. J. Radiol. 75, 24–30.

Towson, J.E.C., Eberl, S., 2006. Radiation protection and dosimetry in PET and PET/CT. In: Positron Emission Tomography. Springer, London, pp. 41–62. https://doi.org/10.1007/1-84628-187-3_4.

Tzampazidou, E., Fotina, A.A., Chatonidis, V., Tsalafoutas, I.A., Datseris, I.E., Samartzis, A., 2021. Patient doses in whole-body PET/CT examinations in the largest tertiary hospital in Greece. Radiat Prot Dosimetry 197, 111–118. https://doi.org/10.1093/rpd/ncab169.

Wachabauer, D., Beyer, T., Ditto, M., Gallowitsch, H.-J., Hinterreiter, M., Ibi, B., Malle, P., Mirzaei, S., Smetana, F., Staudenherz, A., Warwitz, B., Zettinig, G., Rausch, I., 2022. Diagnostic Reference Levels for nuclear medicine imaging in Austria: a nationwide survey of used dose levels for adult patients. Z. Med. Phys. 32, 283–295. https://doi.org/10.1016/j.zemedi.2021.11.007.

Wang, Q., Wang, J., Cao, X., Li, Q., Xie, S., Sang, J., Zhang, Y., Xue, C., Fu, Q., 2023. Preliminary study on diagnostic reference levels of whole-body PET-CT examinations in Jiangsu Province, China. Radiat Prot Dosimetry 199, 1416–1422. https://doi.org/10.1093/rpd/ncad199.

Xiao, J., Yu, H., Sui, X., Hu, Y., Cao, Y., Liu, G., Zhang, Y., Hu, P., Wang, Y., Li, C., Xu, B., Shi, H., 2021. Can the BMI-based dose regimen be used to reduce injection activity and to obtain a constant image quality in oncological patients by 18F-FDG total-body PET/CT imaging? Eur J Nucl Med Mol Imaging 49, 269–278. https://doi.org/10.1007/S00259-021-05462-5.

Xie, T., Zanotti-Fregonara, P., Edet-Sanson, A., Zaidi, H., 2018. Patient-specific computational model and dosimetry calculations for PET/CT of a patient pregnant with twins. J. Nucl. Med. 59, 1451–1458. https://doi.org/10.2967/jnumed.117.205286.