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FULL PAPER

An Australian local diagnostic reference level for paediatric whole-body ^{18}F-FDG PET/CT

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Objective: The aim of this study is to report a local diagnostic reference level (DRL) for paediatric whole-body (WB) fludeoxyglucose (^{18}F-FDG) positron emission tomography (PET) CT examinations.
Methods: The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) national DRL (NDRL) age category (0–4 years and 5–14 years), the International Commission on Radiological Protection age category (ICRP age) (<1, >1–5, >5–10, and >10–15 years), and European guideline weight category (EG weight) (<5, 5–<15, 15–<30, 30–<50, and 50–<80 kg) were used to determine a local DRL for WB ^{18}F FDG PET/CT studies. Two-structured questionnaires were designed to collect dose data, patient demographics, equipment details, and acquisition protocols for WB ^{18}F-FDG PET/CT procedures. The local DRL was based on the median ^{18}F-FDG administered activity (MBq), dose–length product (DLP), and the CT dose index volume ($CTDI_{vol}$), values. The effective dose (E) was also calculated and reported.
Results: The local DRLs for ^{18}F-FDG administered activity, $CTDI_{vol}$ and DLP values based on ARPANSA age and ICRP age were increased from lower to higher age categories. For the EG weight category, the local DRL for ^{18}F-FDG administered activity, $CTDI_{vol}$ and DLP values were increased from the low EG weight category to the high EG weight category. The mean administered activity in our study based on ICRP age category >1–5, >5–10, and >10–15 years is 79.97, 119.40, and 176.04 MBq, which is lower than the mean administered activity reported in the North American Consensus guideline published in 2010 (99, 166, and 286 MBq) and European Association of Nuclear Medicine and Dosage Card (version 1.5.2008) (120, 189, and 302 MBq). However, the mean administered activity in our study based on ICRP age category <1 year was 55 MBq compared to the EANM Dosage card (version 1.5.2008) (70 MBq) and the NACG 2010 (51 MBq). Our study shows that the finding for ICRP age category <1 year was similar to the NACG 2010 value.
Conclusion: The determined local DRL values for the radiation doses associated with WB ^{18}F FDG PET/CT examinations are differed considerably between the ARPANSA and ICRP age category and EG weight category. Although, the determined ^{18}F-FDG value for ICRP < 1 year is in good agreement with available publish data, it is preferable to optimise the ^{18}F-FDG administered activity while preserving the diagnostic image quality.
Advances in knowledge: The local DRL value determined from WB ^{18}F-FDG PET/CT examinations may help to establish the ARPANSA NDRL for WB FDG ^{18}F-PET/CT examinations.

INTRODUCTION

Positron emission tomography combined with X-ray CT (PET/CT) is a powerful hybrid imaging modality that enables exploration of numerous common illnesses, particularly in oncology and neurology.[1] The radiation burden delivered as a result of PET/CT examination needs to be considered to mitigate the risk of inducing cancer, particularly for paediatric patients undergoing multiple PET/CT examinations over the course of their disease.[2] Paediatric patients are more susceptible to radiation-induced cancers than adult patients due to the fast cell division associated with growth and the longer life expectancy of paediatrics.[3] The National Academy of Sciences showed the carcinogenic risk for a 1-year-old infant and a 10-year-old child was to be three and two times higher than that of a 40-year-old adult patient. Therefore, to minimise the risk of inducing cancer,

it is important to justify PET/CT examinations, optimise radiation doses while maintain diagnostic image quality, and have established diagnostic reference levels (DRLs) when performing PET/CT.[1]

Different paediatric grouping categories were identified for paediatric NDRL methods for medical imaging examinations. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) used two age categories (0–4 and 5–14 years old) for their multidetector CT paediatric national DRL (NDRL) survey.[4] Hayton et al. stated the ARPANSA age bands were selected to match bands used by the Medicare Benefits Schedule data to match procedure frequency data and to avoid the impede of the data collection.[5] However, the European guideline (EG), and International Commission on Radiological Protection (ICRP) demonstrate that special consideration is needed in the grouping paediatric NDRLs survey.[6,7] This is because the paediatric habitus varies by approximately 100 kg between a premature infant (<1 kg) and a large adolescent (>100 kg).[8] The paediatric DRL audits often utilise the ICRP age band categories (<1, >1–5, > 5–10, and >10–15 years). A recent weight band category introduced by EG weight (<5, 5–<15, 15–<30, 30–<50, and 50–<80 kg), which is an approximate equivalent population as the ICRP age band category.[8] The EG weight to ICRP age range equivalence should only be used when comparing the EG weight DRL with previously published ICRP age DRLs.[6,7] The ICRP 135 recommends the EG weight band category is more appropriate for determining paediatric DRL because weight is more strongly correlated to dose than age.[6] However, utilising the ICRP age category is still valid if the age is the only available category during NDRL audit.[6] For examinations involving the head, age groupings instead of weight are recommended to establish DRL values.[8]

Published paediatric NDRL methods do not the follow the above recommended paediatric grouping categories for determining NDRL based on 75th percentile for PET/CT examinations. The Australian and New Zealand Society of Nuclear Medicine (ANZSNM) determined the paediatric DRL for whole-body (WB) and brain fludeoxyglucose (^{18}F-FDG) PET examinations. Their reported DRL was based on the median of the minimum administered activity (A_{min}) and the median of the maximum administered activity (A_{max}) rather than the 75th percentile method.[9] This method was chosen due to a small number of paediatric patients and the existence of outlier values for some nuclear procedures identified in the survey.[9] The ANZSNM survey demonstrated that there is a large variation between the A_{min} (18-fold) and A_{max} (20-fold) which may hinder the derivation of a representative standard for a broad range of paediatric habitus for neonates to adeloscents.[10] Moreover, in France, four ^{18}F FDG administered activity values for WB ^{18}F-FDG PET DRL values were adopted from the European Association of Nuclear Medicine (EANM) guidelines for four weight groups without providing the range. The paediatric patients weight (kg) categories are 3.5, 10, 20, 30, and 40 and corresponding administered activity (MBq) are 15, 40, 70, 100, and 125, respectively.[10] This DRL method is limited due to use of adopting guidelines rather than collecting radiation dose metrics and determining the French NDRL from PET/CT clinical practice. The published French paediatric DRL data does not reflect the paediatric habitus from neonate to adolescent.

The current 2017 updated ARPANSA NDRL did not include a PET/CT DRL for paediatric patients.[11] Likewise, no international DRL audits have been carried out for paediatric ^{18}F-FDG PET/CT examinations. Additionally, no national or international DRL audit was performed to derive the DRL for the CT component associated with WB ^{18}F-FDG PET/CT examinations. The purpose of this work is to report an Australian paediatric WB ^{18}F-FDG PET/CT local DRL following national and international paediatric DRL methods.

METHODS AND MATERIALS

Ethical approval was gained from the paediatric hospital's Human Research Ethics Committee (LNR/16/****/289) to collect anonymised data from the participating site. In this retrospective study, 300 paediatric WB ^{18}F-FDG PET/CT cases were selected from one centre. The maximum administered activity for the participant centre based on adult reference (200 MBq) and the PET/CT scanner did not change during the period of data collection between 2012 until 2018. Paediatrics between the ages 0 and 15 years old who had undergone WB ^{18}F-FDG PET/CT between August 2012 and March 2017 were included in this study. The data collection was extended to May 2018 for ICRP age "<1 year old" due to insufficient number of paediatric patients in this category (three patients only). The first questionnaire was designed to collect the equipment manufacturer, model, commission date, hardware and software technology and PET/CT acquisition protocol. For the second questionnaire, the PET/CT technologists were asked to record patient demographic information, ^{18}F-FDG administered activity, CT dose index volume ($CTDI_{vol}$) and dose–length product (DLP) (Supplementary Material [Table 4]). A copy of the department's WB ^{18}F-FDG PET/CT acquisition protocols were also requested from the participating centre. All patient dose data was retrieved from the Picture Archiving Communication System. Local DRLs were established for babies/infants from 0 to 4 years and children from 5 to 14 years following ARPANSA age NDRL method for multidetector CT for paediatric population. DRLs were also classified for four ICRP age band categories, <1 year, >1–5 years, >5–10 years, >10–15 years and five EG weight bands <5, 5–<15, 15–<30, 30–<50, and 50–<80 kg. The DRL value was reported for collection of a minimum of 10 patients for each ARPANSA age, ICRP age, and EG weight band categories.

Effective dose (E) was calculated for the PET and CT procedures separately. For ^{18}F-FDG, E was calculated using the effective dose coefficients defined by ICRP 128 for Year 1 (0.095 mSv/MBq), Year 5 (0.056 mSv/MBq), Year 10 (0.037 mSv/MBq), and Year 15 (0.024 mSv/MBq).[12] For CT, E was calculated using the National Cancer Institute dosimetry system for CT (NCICT) software (NIH Ref. No. E-082-2016/0) and the effective dose coefficients published in ICRP 103. The E for ^{18}F-FDG administered activity (E PET) is calculated as follow:

E_{PET} = administered activity ×effective dose coefficient (ICRP128)

For the CT part, NCICT calculates organ dose which can be directly used to derive E. The DLP-to-E conversion coefficients are not used.[13] The overall E from WB ^{18}F-FDG PET/CT examination is the sum of the E_{PET} and E_{CT} derived from NCICT software:

$E_{Total} = E_{PET} + E_{CT}$ (NICICT organ dose calculation).

DRLs are recognised as valuable for continuously monitoring of radiation doses delivered across diverse medical imaging examinations. An established DRL can provide clear guidance to support dose optimisation strategies.[6] Establishing an NDRL requires the exploration the range and distribution of radiation doses delivered by numerous sites and devices through variations in acquisition protocols at participating clinical facilities. The NDRL numerical value for radiation dose quantity is derived from the 75th percentile of the distribution of median doses from the dose audit of participating facilities.[6,14] The establishment of DRL at a clinical facility is referred to as local diagnostic reference level (local DRL).[6,15] Local DRLs are derived from the median of the distribution of local doses rather than from the 75th percentile. The local DRLs' numerical values should be regularly reviewed and compared against NDRL standards to ensure that radiation doses delivered are below, or at least equivalent to, NDRL standards.[6] In this study, only one PET/CT centre participated in the survey, therefore, the determined DRL for ^{18}F-FDG administered activity, $CTDI_{vol}$ and DLP for CT complement were reported following 50th percentile. Additionally, radiation dose quantities are expressed as a mean ± standard deviation, median (50th percentile), minimum and maximum for the whole distribution of values for the different radiation dose quantities. All statistical analyses were performed for radiation dose quantities using the Statistical Package for the Social Science software (v. 24.0, IBM Corp. Armonk, NY). The local DRL and E results were communicated back to the participating site.

RESULTS

A total of 231 of the 300 patients were included in the ARPANSA age category, 69 patients were excluded due to being more than 14 years old. For the ICRP age category, 282 patients were included with 18 excluded due to their age being >15 years. For the EG weight category, 37 were excluded due to their weight being greater than 80 kg. Four of the five paediatric EG weight categories were identified in this survey. The EG weight category "<5 kg" was excluded due to an insufficient number (7) of paediatric patients to report the local DRL. The patient characteristics for each paediatric category are presented in Table 1. Moreover, most of the identified cases were collected for oncological clinical indications, with 14 cases only performed for infection.

The following describes WB ^{18}F-FDG PET/CT acquisition. The PET acquisition time was 2 min per bed for all of the paediatric categories. The identified PET/CT machine equipped with time of flight technology and Lutetium oxyorthosilicate (LSO) scintillation material. The CT parameters tube voltage of 100 kVp, rotation time of 0.5 s, slice thickness 3 mm, and pitch ratio of 0.8 were fixed for all studies. The mean CT tube current and scan length (cm) for category are shown in Supplementary Material (Table 5). The identified CT component associated with WB ^{18}F-FDG PET/CT was used for the purposes of attenuation correction and anatomical localisation. Four common CT ranges were identified for WB ^{18}F-FDG PET/CT examinations: vertex

Table 1. Paediatric demographic information

Group category	No. of patients	Gender (B/G)	Age (years)	Weight (kg)	Height (cm)	BMI (kg m^{-2})
			Mean (±SD)			
ARPANSA age (years)						
0–4	80	40/40	1.70 (±1.26)	10.34(±4.37)	82.61 (±20.23)	15.75 (±2.87)
5–14	151	94/57	10.62 (±2.74)	41.05 (±18.74)	143.58 (±18.31)	18.85 (±4.48)
Total	231					
ICRP age (years)						
<1	42	24/18	0.69 (±0.46)	7.33 (±1.97)	70.73 (±19.45)	16.03 (±3.32)
>1–5	43	21/22	3.06 (±1.07)	14.10 (±3.90)	97.02 (±15.28)	15.16 (±2.49)
>5–10	61	44/17	8.14 (±1.42)	27 (±6.20)	128.16 (±8.08)	16.23 (±2.22)
>10–15	136	62/74	13.58 (±1.40)	58.19 (±19.97)	159.88 (±12.92)	22.35 (±5.34)
Total	282					
EG weight (kg)						
5–< 15	57	26/31	1.42 (±0.88)	9.27 (±2.02)	77.73 (±12.29)	15.80 (±2.83)
15–< 30	63	43/20	6.61 (±2.21)	21.68 (±3.73)	119.37 (±10.14)	15.19 (±1.68)
30–< 50	67	42/25	11.74 (±2.01)	39.59 (±5.60)	146.90 (±10.63)	18.31 (±1.94)
50–< 80	76	30/46	14.06 (±1.04)	63.04 (±6.79)	164.29 (±8.33)	23.51 (±3.55)
Total	263					

B, Boy; BMI, body mass index; G, Girl; SD, standard deviation.

to feet, base of skull to feet, vertex to thigh, and base of skull to thigh. The vertex-to-feet and base of skull-to-thigh CT scan ranges were the most common CT acquisition protocols, with 191 and 82 performed, respectively. The base of skull-to-feet and vertex to thigh CT scan ranges were the least common CT acquisition protocols, with 5 and 4 performed, respectively. One PET/CT scanner, Biograph mCT (Siemens Healthcare, Knoxville, TN), was used for all studies. The CT was calibrated by the manufacturer using the 32 cm (diam) body phantom. The automatic exposure control capability was utilised for CT acquisition protocols for all patients. The scanner installation data was on June 2012.

The local DRL for ^{18}F-FDG administered activity, administered activity/weight (MBq/kg), $CTDI_{vol}$, and DLP are presented for each paediatric group category in Table 2. The mean E for each category and each radiation dose quantity are also listed in Table 3.

DISCUSSION

This is the first reported local paediatric DRL for WB ^{18}F-FDG PET/CT administered activity (MBq) and CT ($CTDI_{vol}$ and DLP) using age and weight categories following the retrospective data collection method. The literature reveals that adopting a prospective data collection approach during WB ^{18}F-FDG PET/CT examinations was ineffective in determining NDRL for paediatric patients of various ages ranging from neonates to adolescents.[10,16] This was a result of a lack of paediatric patients of those ages available for the NDRL survey. In a study carried out in France, a ^{18}F-FDG PET/CT NDRL was determined for ^{18}F-FDG administered activity for adult patients but not for paediatric patients, due to insufficient paediatric numbers in the 2004 and 2008 surveys.[10] The findings from our study show that the participating centre did not change its method of ^{18}F-FDG administered activity, its CT dose, or its equipment over 5 years. As a result, following a retrospective data collection approach should enable access to more comprehensive data and would overcome the challenge of finding sufficient numbers of paediatric patients, which was an issue in the French NDRL study.[6,10] Thus, the local DRLs based on the ARPANSA age, ICRP age, and EG weight categories were determined, as well as benchmark DRL information for use in future studies on paediatric patients.

This study reports on local DRLs for WB ^{18}F-FDG PET/CT examinations related to two ARPANSA age band categories: baby/infant (0–4 years) and children (5–14 years).[5] However, the determined local DRL method following the ARPANSA age category limits data comparison with other international paediatric categories. This is because the age range for the ARPANSA age category is different than it is for the ICRP age band category.[5] ARPANSA have used prospective data collection approach with two age categories to determine multidetector CT NDRL for paediatrics but not for PET/CT examinations as yet. Thus, in absence of the ARPANSA NDRL for paediatric PET/CT examinations, the data derived from this study may be used as a comparative DRL for Australian PET/CT clinical centres that perform paediatric WB ^{18}F-FDG PET/CT examinations.

This is the first study to determine local DRL values for ^{18}F-FDG administered activity and CT component based on ICRP age groups <1, >1–5, >5–10, and >10–15 years (Table 3). The mean administered activity in our study was lower than mean ^{18}F-FDG values by the North American Consensus Guideline (NACG) 2010 and EANM dosage card (version 1.5.2008) for ICRP age category for >1–5, > 5–10, and >10–15 years (Figure 1).[17] This is because the participating centre used the Gilday's method, and scaled their ^{18}F-FDG administered activity based on an adult reference level (70 kg) of 200 MBq in comparison to 370 MBq and 363 MBq for NACG 2010 and EANM Dosage Cards (version 1.5.2008), respectively.[18,19] It is important to demonstrate that the paediatric administered activity (MBq) following Gilday's method, is determined by weight (kg) and the percentage of the standard adult dose. Standard adult dose is determined according to the adult patients body surface area. Gilday's calculation method enables distribution of administered activity (MBq) per unit area of the organ rather than per kg of body weight.[20] The other reason for lowering the administered activity is that the participant PET/CT centre utilised a PET system equipped with time of flight technology and LSO crystal material, and it administered the MBq/kg according to advances in PET/CT technology. However, the determined mean ^{18}F-FDG administered activity for ICRP age <1 years is less than the mean ^{18}F-FDG administered activity for the EANM dosage card (version 1.5.2008) and almost the same as recommended by NACG 2010 (Figure 1). There is a 4 MBq variation between our study and NACG 2010 for the ICRP age group <1 year. The literature reveals that variation often happens in the ICRP age group <1 year, primarily due to this category including the smallest and youngest paediatric patients. Such variation in administered activity indicates that optimisation of the administered activities and consistent image quality should remain priorities.[18] Importantly, the minimum ^{18}F-FDG administered activity for the participating PET/CT centre is 20 MBq, which is less than the minimum ^{18}F-FDG administered activity for NACG 2016 37 MBq.[21] In some circumstances, the radiation doses may be increased if the patient's body habitus or disease conditions require deviation the radiation dose in the centre's protocol.[14] The participating PET/CT centre scaled its ^{18}F-FDG administered activity based on an adult reference level of 200 MBq. Attempting to reduce the ^{18}F-FDG administered activity, therefore, is highly recommended without compromising diagnostic image quality.

The EG demonstrate that using a weight category is more practical in paediatric groupings of DRLs in medical imaging procedures due to the wide variation in paediatric habitus at given age.[6–8] In clinical practise, weight is accessible and recorded routinely in PET/CT and NM examinations so as to adjust administered activities according to patient weight. This is not the case in radiology, where weight may not be captured routinely during CT alone. Moreover, the EG introduced an appropriate equivalence of weight and age groups to compare weight-based DRLs with previously published age-based DRLs.[7,8] The literature reveals the absence of DRLs for paediatric WB ^{18}F-FDG PET/CT examinations to determine a DRL based on the ICRP age category. This study determined a local DRL based on both the

Table 2. Radiation dose measurements for paediatric WB ^{18}F-FDG PET/CT age and weight categories

Patient group	Administered activity (MBq)				Administered activity/weight (MBq/kg)				$CTDI_{vol}$ (mGy)				DLP (mGy.cm_)			
	Mean (±SD)	Median	Min	Max	Mean (±SD)	Median	Min	Max	Mean (±SD)	Median	Min	Max	Mean (±SD)	Median	Min	Max
ARPANSA age																
0–4	66.16 (19.44)	63.63	29.75	133.73	6.88 (2.06)	6.47	0.64	13.95	0.64 (0.24)	0.59	0.44	2.41	59.38 (31.33)	52.00	28.00	241.00
5–14	146.84 (35.74)	144.22	82.45	241.19	3.91 (0.87)	3.87	1.50	6.21	1.29 (0.60)	1.06	0.41	3.84	170.23 (98.04)	151.00	48.00	769.00
ICRP age																
<1	55.28 (12.71)	55.66	29.75	97.74	7.77 (2.29)	7.54	0.64	13.95	0.54 (0.08)	0.53	0.44	0.84	45.02 (17.75)	43.00	28.00	138.00
>1–5	79.97 (18.65)	77.54	38.62	133.73	5.83 (1.10)	5.58	3.86	9.18	0.75 (0.29)	0.69	0.49	2.41	75.72 (33.43)	69.00	34.00	241.00
>5–10	119.40 (17.53)	116.19	84.33	173.80	4.53 (0.67)	4.40	3.27	6.21	0.91 (0.18)	0.89	0.64	1.45	110.14 (31.21)	108.00	48.00	218.00
>10–15	176.04 (26.05)	179.90	88.07	241.19	3.20 (0.61)	3.12	1.48	5.55	2.30 (5.82)	1.66	0.41	69.00	248.47 (134.11)	221.00	72.00	941.00
EG weight																
5–< 15	62.34 (12.00)	60.86	38.04	101.62	6.90 (1.48)	6.71	3.86	11.64	0.61 (0.25)	0.57	0.47	2.41	56.52 (30.14)	52.00	29.00	241.00
15–<30	106.26 (14.32)	107.58	74.81	140.83	4.97 (0.68)	4.92	3.27	7.11	0.83 (0.12)	0.81	0.64	1.16	92.87 (23.62)	95.00	48.00	137.00
30–<50	148.29 (19.35)	150.33	88.07	184.94	3.76 (0.36)	3.82	2.69	4.83	1.17 (0.30)	1.08	0.41	2.02	156.74 (32.72)	160.00	90.00	227.00
50–<80	187.07 (22.24)	189.59	43.58	241.19	2.98 (0.38)	2.98	0.64	3.74	1.98 (0.60)	1.95	0.57	3.74	252.61 (64.96)	240.50	42.00	435.00

ARPANSA, Australian Radiation Protection and Nuclear Safety Agency; $CTDI_{vol}$, CT dose index volume; EG, European guideline; ^{18}F-FDG, 18-fludeoxyglucose; ICRP, International Commission on Radiological Protection; PET, positron emission tomography; CT, computed tomography; SD, standard deviation.

Table 3. Summary of effective dose (mSv) data for WB ^{18}F-FDG paediatric age and weight categories

Patient group	PET (mSv)	CT (mSv)	PET/CT (mSv)
	Mean		
ARPANSA age (years)			
0–4	4.83	1.83	6.67
5–14	4.25	2.79	7.04
ICRP age (years)			
<1	5.25	1.49	6.75
>1–5	4.47	2.13	6.61
>5–10	4.41	2.15	6.56
>10–15	4.22	3.46	7.68
EG weight (kg)			
5– < 15	4.85	1.69	6.55
15–< 30	4.40	2.08	6.49
30–< 50	4.08	2.34	6.43
50–< 80	4.53	3.70	8.23

ARPANSA, Australian Radiation Protection and Nuclear Safety Agency; CT, computed tomography; EG, European guideline; ^{18}F-FDG, 18-fludeoxyglucose; ICRP, International Commission on Radiological Protection; PET, positron emission tomography.

EG weight and ICRP aged categories and compared the results. The finding in our study shows that the determined local DRL value following the EG weight category is higher than in the ICRP age category. This is because the weights of patients in each EG weight category were higher than the patient weights in each ICRP age category (Table 1). Table 2 shows that the determined DRL values for ^{18}F-FDG administered activity, $CTDI_{vol}$, and DLP for the paediatric EG weight and ICRP age categories were not equivalent. Only 63%, 32%, and 30% of data of the EG weight and ICRP age categories are equivalent within the first three groups. The paediatric patients observed in our study varied in size. It was difficult to find standard-sized paediatric patients who fit the recommended criteria of EG weight category for a given ICRP age category. Thus, future NDRL for paediatric WB ^{18}F-FDG PET/CT examinations should benchmark and determine

Figure 1. Comparisons of mean ^{18}F-FDG administered activity with a recommended mean EANM Dosage Card (version 1.5.2008) and NACG 2010 international guidelines. ^{18}F, 18-fludeoxyglucose; EANM, European Association of Nuclear Medicine; NACG, North American Consensus Guideline.

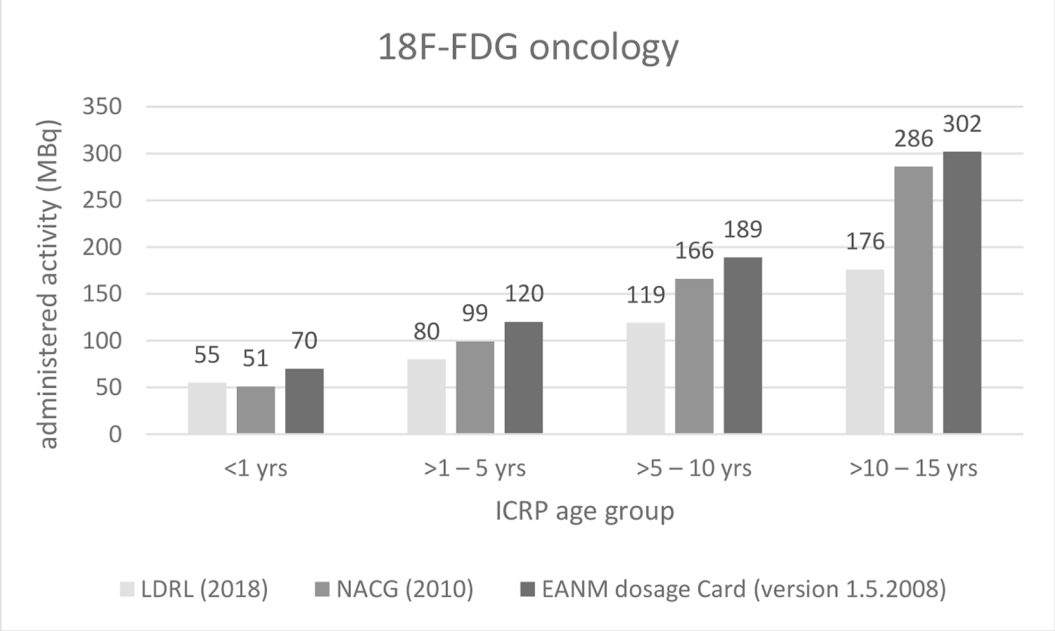
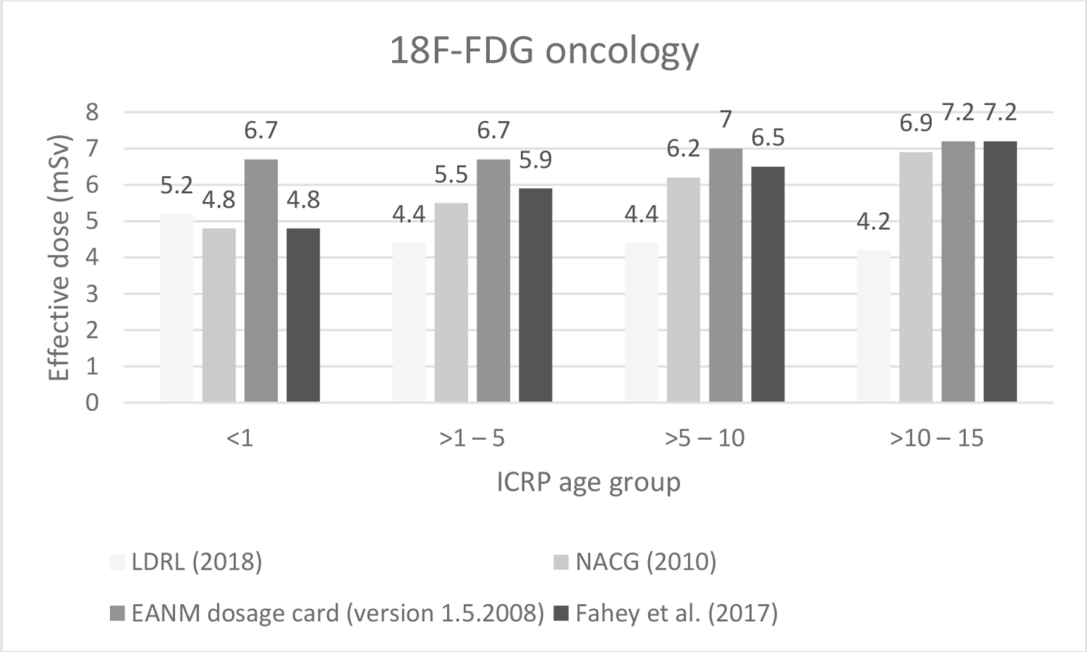


Figure 2. Comparisons of LDRL effective dose with published guidelines and dose estimates in paediatric nuclear medicine for WB ^{18}F-FDG PET.[22,23] ^{18}F-FDG, 18-fludeoxyglucose; WB, whole-body.



DRLs according to the EG weight category equivalent to ICRP age category.

The effective dose (E) has been reported for different local DRL age and weight categories in Table 3. The major contribution of the total radiation dose was from administered activity for all local DRL categories. The reported E value for paediatric ^{18}F-FDG administered activity for ARPANSA age 0–4, ICRP age <1 and EG weight five to <15 kg categories was higher among the identified categories. This is because the administered activity is weight-independent for some patients in these categories as a minimum injected activity of 29.75 MBq is required for diagnostic image quality. The other reason would be that the ICRP 128 use different value (mSv MBq^{-1}) for calculating the E for paediatric age 1, 5,10, and 15 years old. For international data comparisons, Figure 2 showed that the E value from the mean ^{18}F-FDG administered activity for ICRP age category (>1–5, >5–10, >10–15) was lower than NACG 2010, EANM Dosage Card (version 1.5.2008), and Fahey et al. (2017) for paediatric age category groups.[22,23] This is because the participating centre scaled the administered activity based on an adult reference (200 MBq), and their PET/CT used time-of-flight technology, which assists in dose reduction for the patients without compromising diagnostic image quality.[24] For paediatric ICRP age <1 year, the E from mean ^{18}F-FDG administered activity was less than the EANM Dosage Card (version 1.5.2008) and an approximate to the NACG 2010 and Fahey et al. mean E for ^{18}F-FDG administered activity (Figure 2). Furthermore, for CT component, NICCT calculates the E value by organ dose to derive the E value for whole-body CT scan. The E value for the CT increased gradually with increasing paediatric age and weight, for all categories, because the mAs value increased with increased body weight and DLP increased with scan length as seen in Tables 1 and 2.

LIMITATIONS

This study has some recognised limitations. The data analysis was conducted on paediatric patient groups from a single clinical facility, therefore the local DRL values are specific to the participating centre and might not represent general and dedicated paediatric PET/CT centres throughout Australia. Another limitation is that the DRL data reported is based on data collected from 2012 to 2018. This is not a standard approach for DRL data acquisition. It was only possible due the centre having used the same equipment and PET and CT doses over this long period. In addition, this study was unable to determine the DRL for the paediatric weight category <5 kg due to an insufficient patient sample in this weight group.

CONCLUSIONS

This is the first Australian study to determine local DRL value for WB ^{18}F-FDG PET/CT examinations following the ARPANSA age categories for paediatric populations. The value determined from our study can be used by other PET/CT facilities to compare their median radiation doses with those reported following age or weight categories. The administered activity of ^{18}F-FDG and E for the paediatric ICRP age group is less than presented in the available published data for the ICRP age categories (>1–5, >5–10 and >10–15 years). The ^{18}F-FDG administered activity for ICRP age <1 year has good agreement with the published peer data. Focusing on image quality rather than the amount of ^{18}F-FDG administered activity should be a greater priority in the additional optimisation process. A follow-up local DRL is essential to explore the variation between radiation doses and to reach a desirable dose for ICRP age <1 year following the centre's protocol.

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REFERENCE

1. Fahey FH, Goodkind A, MacDougall RD, Oberg L, Ziniel SI, Cappock R, et al. Operational and Dosimetric aspects of pediatric PET/CT. *J Nucl Med* 2017; **58**: 1360–6. doi: https://doi.org/10.2967/jnumed.116.182899
2. Chawla SC, Federman N, Zhang D, Nagata K, Nuthakki S, McNitt-Gray M, et al. Estimated cumulative radiation dose from PET/CT in children with malignancies: a 5-year retrospective review. *Pediatr Radiol* 2010; **40**: 681–6. doi: https://doi.org/10.1007/s00247-009-1434-z
3. Hwang JY, Do KH, Yang DH, Cho YA, Yoon HK, Lee JS, et al. A survey of pediatric CT protocols and radiation doses in South Korean hospitals to optimize the radiation dose for pediatric CT scanning. *Medicine* 2015; **94**: e2146. doi: https://doi.org/10.1097/MD.0000000000002146
4. Current Australian national diagnostic reference levels for MDCT. 2017. Available from: https://www.arpansa.gov.au/research/surveys/national-diagnostic-reference-level-service/current-diagnostic-reference-levels.
5. Hayton A, Wallace A. Derivation of Australian diagnostic reference levels for paediatric multi detector computed tomography. *Australas Phys Eng Sci Med* 2016; **39**: 615–26. doi: https://doi.org/10.1007/s13246-016-0431-4
6. Vañó E, Miller DL, Martin CJ, Rehani MM, Kang K, Rosenstein M, et al. ICRP publication 135: diagnostic reference levels in medical imaging. *Ann ICRP* 2017; **46**: 1–144. doi: https://doi.org/10.1177/0146645317717209
7. European Guidelines on DRLs for Paediatric Imaging. 2016. Available from: http://www.eurosafeimaging.org/wp/wp-content/uploads/2014/02/European-Guidelines-on-DRLs-for-Paediatric-Imaging_Revised_18-July-2016_clean.pdf.
8. Commision E. *Radiation protection No 185. European guideline on diagnostic reference levels for paedatric imaging*. Luxembourg: Publications Office of the European Union: European commission; 2018.
9. Towson JE, Smart RC. Diagnostic reference activities for nuclear medicine procedures in Australia and New Zealand. *ANZ Nuclear Medicine* 2000; **31**: 23–30.
10. Roch P, Aubert B. French diagnostic reference levels in diagnostic radiology, computed tomography and nuclear medicine: 2004-2008 review. *Radiat Prot Dosimetry* 2013; **154**: 52–75. doi: https://doi.org/10.1093/rpd/ncs152
11. Australian Radiation Protection and Nuclear Safety Agency. Nuclear Medicine/PET diagnostic reference levels 2017. 2018. Available from: https://www.arpansa.gov.au/research/surveys/national-diagnostic-reference-level-service/modality-surveys/nuclear-medicine-pet-diagnostic-reference-levels [cited 2018 June].
12. Mattsson S, Johansson L, Leide Svegborn S, Liniecki J, Noßke D, Riklund KÅ, et al. Radiation dose to patients from radiopharmaceuticals: a compendium of current information related to frequently used substances. *Ann ICRP* 2015; **44**(2 Suppl): 7–321. doi: https://doi.org/10.1177/0146645314558019
13. Lee C, Kim KP, Bolch WE, Moroz BE, Folio L. NCICT: a computational solution to estimate organ doses for pediatric and adult patients undergoing CT scans. *J Radiol Prot* 2015; **35**: 891–909. doi: https://doi.org/10.1088/0952-4746/35/4/891
14. Alkhybari EM, McEntee MF, Brennan PC, Willowson KP, Hogg P, Kench PL. Determining and updating PET/CT and SPECT/CT diagnostic reference levels: a systematic review. *Radiat Prot Dosimetry* 2018; **182**: 532–45. doi: https://doi.org/10.1093/rpd/ncy113
15. Brady Z, Ramanauskas F, Cain TM, Johnston PN. Assessment of paediatric CT dose indicators for the purpose of optimisation. *Br J Radiol* 2012; **85**: 1488–98. doi: https://doi.org/10.1259/bjr/28015185
16. Botros GM, Towson JE, Smart RC. Updated paediatric diagnostic reference activities for nuclear medicine procedures in Australia and New Zealand derived from the 2009 survey. *ANZ Nuclear Medicine* 2010; **41**: 12.
17. Lassmann M, Treves ST, .EANM/SNMMI Paediatric Dosage Harmonization Working Group Paediatric radiopharmaceutical administration: harmonization of the 2007 EANM paediatric dosage CARD (version 1.5.2008) and the 2010 North American consensus guidelines. *Eur J Nucl Med Mol Imaging* 2014; **41**: 1036–41. doi: https://doi.org/10.1007/s00259-014-2731-9
18. Gelfand MJ, Parisi MT, Treves ST, .Pediatric Nuclear Medicine Dose Reduction Workgroup Pediatric radiopharmaceutical administered doses: 2010 North American consensus guidelines. *J Nucl Med* 2011; **52**: 318–22. doi: https://doi.org/10.2967/jnumed.110.084327
19. Goetz WA, Hendee WR, Gilday DL. In vivo diagnostic nuclear medicine. pediatric experience. *Clin Nucl Med* 1983; **8**: 434–9.
20. Britton KE, Maisey M, Collier D. *Clinical nuclear medicine*. 3rd ed. London, Melbourne: Chapman & Hall Medical; 1998.
21. Treves ST, Gelfand MJ, Fahey FH, Parisi MT. Update of the North American consensus guidelines for pediatric administered radiopharmaceutical activities. 2016; **57**: 15N–18. doi: https://doi.org/15N-18N
22. Grant FD, Gelfand MJ, Drubach LA, Treves ST, Fahey FH. Radiation doses for pediatric nuclear medicine studies: comparing the North American consensus guidelines and the pediatric dosage Card of the European association of nuclear medicine. *Pediatr Radiol* 2015; **45**: 706–13. doi: https://doi.org/10.1007/s00247-014-3211-x
23. Fahey FH, Goodkind AB, Plyku D, Khamwan K, O'Reilly SE, Cao X, et al. Dose estimation in pediatric nuclear medicine. *Semin Nucl Med* 2017; **47**: 118–25. doi: https://doi.org/10.1053/j.semnuclmed.2016.10.006
24. Kwon HW, Kim JP, Lee HJ, Paeng JC, Lee JS, Cheon GJ, et al. Radiation dose from whole-body F-18 fluorodeoxyglucose positron emission tomography/computed tomography: nationwide survey in Korea. *J Korean Med Sci* 2016; **31 Suppl 1**: S69–S74. doi: https://doi.org/10.3346/jkms.2016.31.S1.S69