Estimation of effective dose for whole body $^{18}$F-FDG PET/CT examination

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Abstract. Whole body flourine-$^{18}$fluoro-2-deoxy-D-glucose ($^{18}$F-FDG) positron emission tomography/computed tomography (PET/CT) is part of the standard management of oncoligic diagnosis and staging. However, there is a growing concern over the radiation exposure of patient undergoing PET/CT due to higher radiation dose compared to other imaging modalities. The aim of this study is to estimate the effective dose received by 104 patients that undergone a whole body $^{18}$F-FDG PET/CT at the University of Malaya Medical Centre (UMMC). The effective dose from CT were calculated using two methods, namely, dose length product (DLP) method as recommended by International Commission on Radiological Protection (ICRP) Publication 102 and size specific dose estimates (SSDE) method as recommended by American Association of Physicist in Medicine, AAPM Report No. 204. Meanwhile, for PET dosimetry, the effective dose resulting from the radiopharmaceutical injection was estimated by means of the model proposed by ICRP Publication 106. The average effective dose for a whole body $^{18}$F-FDG PET/CT examination was found to be 14.82 ± 3.2 mSv for DLP method and 9.47 ± 1.5 mSv for SSDE method. DLP method shows over estimated effective dose because average malaysian population is smaller than reference Perspex phantom which is 32 cm diameter. From this study, estimates lifetime attribute risk (LAR) based on BEIR VII report is only 0.09% for SSDE method compare to DLP method which is 0.14%.

1. Introduction

Positron emission tomography integrated with computed tomography (PET/CT) has emerged as a powerful imaging tool for the detection of various cancers. The combination of PET and CT has advantages over PET or CT alone and minimises their individual limitations. It is a valuable tool for cancer staging and has an important role in the detection of recurrence in asymptomatic patients with rising tumour marker levels and patients with negative or equivocal findings on conventional imaging techniques. The most common radionuclide used for PET imaging is flourine-18-fluoro-2-deoxy-D-glucose ($^{18}$F-FDG) with a half-life of 109.7 minutes. The radionuclide is formed through radiochemical synthesis using a cyclotron, and decays to stable oxygen-18.

For whole body PET/CT examination, the relative contribution of PET and CT dose has been reported to vary, with the CT component contributing between 54 to 81% of the total combined dose,
depending on the CT parameters with the same scan length. The term whole body protocol has been used to cover different body extensions: from vertex to mid-thighs, base of skull to upper thighs, and head to feet, thus complicating direct cross comparisons between centres and studies [1–3]. This study attempts to estimate patient specific effective dose from whole body PET/CT examinations at UMMC. The dosimetric impact of scan length, patient body weight, patient effective diameter, injected activity, CT dose index (CTDI), and dose length product (DLP) were studied.

2. Materials and methods
PET/CT image set of 104 adult patients who underwent $^{18}$F-FDG examinations during the period of April 2018 to June 2018 were collected. The patients were scanned using a Philips Ingenuity Time-of-Flight (TF) 64-slice system (Philips, Amsterdam, Netherlands). All patients were injected with 3.5MBq/kg of $^{18}$F-FDG activity 60 minutes before the whole body PET/CT examination. PET scan was acquired for 1 minute 30 second per bed position (6-10 bed positions in total), from base of skull to the upper thigh. For CT acquisition, the protocol was selected based on patient body mass index (BMI) and the tube current-time product was varied using the automatic exposure control (AEC) technique. The average acquisition time for a whole body PET/CT examination was 20 minutes. A phantom study was carried out to measure organ doses. An adult female anthropomorphic phantom (ATOM phantom, CIRS, Norfolk, VA) inserted with optically stimulated luminescence detectors (OSLDs) (Landauer, Glenwood, IL) at 14 selected organ positions was used. For this study, the average patient age, body weight, scan length, patient effective diameter, $^{18}$F-FDG injected activity was 56.1 ± 15.4 years, 60.4 ± 14.2 kg, 105.6 ± 12.9 cm, 25.1 ± 3.0 cm, and 211 ± 49.7 MBq.

2.1 CT Dosimetry
Effective dose from CT was calculated using two different methods: (i) the simple DLP method [4] and (ii) SSDE method [5].

2.1.1 Dose length product, DLP method. The effective dose was estimated from DLP values provided by the CT scanner, which represent radiation exposure to the entire scan length. The effective dose was calculated using (Eq.1)

$$ED_{DLP} = DLP \times k$$  \hspace{1cm} (Eq.1)

Where $k$ is the coefficient based on empirical weighting factor proposed by ICRP 102, which is dependent on the anatomical region scanned. It has a unit of mSv.mGy$^{-1}$.cm$^{-1}$ and $k$ of 0.015 was used for the trunk region.

2.1.2 Size specific dose estimates, SSDE method. Current CT scanner are able to display volume computed tomography dose index (CTDI$_{vol}$) and dose length product (DLP). Both CTDI$_{vol}$ and DLP are sensitive to changes in scan parameters such as tube voltage, tube current, gantry rotation time, pitch, bowtie filter. They are however independent of the patient’s size. According to the AAPM Report 204, “for smaller paediatric patients, interpreting the displayed CTDI$_{vol}$ or (DLP) as patient dose could lead to underestimation of patient dose level by a factor of 2-3 if the 32cm PMMA phantom was used as a reference”. Therefore, patient size must be taken into account for accurate patient dose estimates.

OSLDs were used to empirically measure organ dose in selected organ in an adult female anthropomorphic phantom (Figure 1). A total of 14 organ doses were studied: brain, skin, thyroid, oesophagus, red bone marrow, lung, liver, bone surface, stomach, colon, ovaries, testes, bladder and breast. The phantom scan and organ dose measurements were repeated thrice. The mean and 1 standard deviation of the absorbed dose measured in the organs were reported.
Figure 1. Absorbed dose received by 14 different organ was measured using optically stimulated luminescence dosimeters (OSLDs) placed inside an adult female anthropomorphic phantom.

The phantom and patient effective diameter was calculated using the formulation described in AAPM Report 204 (Eq. 2):

$$\text{effective diameter} = (\text{AP} \times \text{LAT})^{\frac{1}{2}} \quad \text{(Eq. 2)}$$

where, anteroposterior (AP) and lateral (LAT) dimension measurements are made from the CT images as shown in Figure 2, at approximately midway through the phantom chest and abdomen which correspondent to the largest slice in their respective scan regions.

Figure 2. Effective diameter was measured from the CT image.

Moore et al. [6] has introduce dose correlation factor, \(C_{\text{SSDE}}^{\text{organ}}\) to obtain the correlation between organ dose and SSDE for each organ (Eq.3):

$$C_{\text{SSDE}}^{\text{organ}} = \frac{D_{\text{phantom} \text{ organ}}}{SSDE_{\text{phantom}}} \quad \text{(Eq.3)}$$

where \(D_{\text{phantom} \text{ organ}}\) is the absolute organ dose measured using OSLDs inserted in the physical anthropomorphic phantom and \(SSDE_{\text{phantom}}\) calculated using (Eq. 4):

$$SSDE_{\text{patient or phantom}} = CTDI_{\text{vol}} \times f_{\text{size}} \quad \text{(Eq.4)}$$

The effective diameter measured from (Eq. 2) was used to look up the coefficient conversion factor, \(f_{\text{size}}\) to scale the CTDI\(_{\text{vol}}\) values calculated using 32 cm diameter CTDI phantom from the AAPM Report 204. Dose to the patient organ and effective dose were then calculated using (Eq.5) and (Eq.6):

$$D_{\text{organ} \text{ patient}} = C_{\text{SSDE}}^{\text{organ}} \times SSDE_{\text{patient}} \quad \text{(Eq.5)}$$
\[ ED_{SSDE} = \sum \left[ w_{\text{organ}} \times D_{\text{patient}}^{\text{organ}} \right] \]  
\hspace{1cm} (Eq.6)

where \( w_{\text{organ}} \) is the tissue weighting factor based on ICRP 103 report [7].

2.2 PET Dosimetry
The effective dose from PET is determined using (Eq.7):

\[ ED_{PET} = A \times \gamma_{\text{ED}}^{\text{FDG}} \]  
\hspace{1cm} (Eq.7)

where, \( A \) is injected activity in MBq and \( \gamma_{\text{ED}}^{\text{FDG}} \) is the dose coefficient for the effective dose of \(^{18}\text{F}-\text{FDG}\) which is 0.019 mSv MBq\(^{-1}\) for adult [8].

3. Results and discussion
Table 1 show the CT scan parameter used for this study according to body mass index (BMI) of the patient.

| Parameter           | BMI < 19 | 20 < BMI < 27 | BMI > 28 |
|---------------------|----------|---------------|----------|
| Tube voltage (kVp)  | 100      | 120           | 120      |
| Average tube current (mA) | 349   | 210           | 210      |
| Rotation time (sec)  | 0.5      | 0.5           | 0.5      |
| Scan time (sec)      | 12.6     | 12.6          | 12.6     |
| Collimation          | 64x0.625 | 64x0.625     | 64x0.625 |
| Pitch               | 0.828    | 0.828         | 0.828    |
| DoseRight Index      | 20       | 20            | 20       |

3.1 CT effective dose estimation
The simple DLP method may cause under or overestimation of patient dose when there is a mismatch between the actual body size of the patient and the 32 cm diameter perspex CTDI phantoms. The SSDE method takes into consideration corrections based on patient’s size. The mean effective dose for CT calculated using DLP method was found to be 10.8 ± 3.1 mSv, meanwhile only 5.45 ± 1.2 mSv by using SSDE method. CT Effective dose calculated using SSDE method is 40.2% lower compare to the DLP method. DLP value based on a 32 cm diameter Perspex phantom overestimated the effective dose of the whole body scan for individual patients. The average patient effective diameter in this study was only 25.1 ± 3.0 cm, resulting in a markedly lower effective dose estimates.

3.2 Phantom organ dose and SSDE correlation factor
The correlation factors, \( C_{\text{SSDE}}^{\text{organ}} \) were used to estimate patient organ dose by multiplying the value with patient specific SSDE and individual tissue weighting factor recommended by ICRP 103. Table 2 shows the \( C_{\text{SSDE}}^{\text{organ}} \) for the 14 organs. For organ between chest & abdominopelvic, their correlation factor are on average near unity (1.05; range 0.6-1.5) which demonstrate that SSDE may be useful in estimation more accurate organ dose. Fourteen organ doses measured for anthropomorphic phantom and patient are tabulated in Table 3. Testes received the highest absorbed dose for phantom which is 6.6 mGy and 17.6 mGy for patient. Meanwhile, the red bone marrow received the lowest absorbed dose which is 2.3 mGy for phantom and 4.0 mGy for patient.
Table 2. Correlation factor for 14 measured organ

| Organ                  | $\text{CF}^\text{organ}_{\text{SSDE}}$ | $\text{D}^\text{organ}_{\text{phantom}}$ (mGy) | $\text{D}^\text{organ}_{\text{patient}}$ (mGy) |
|------------------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Brain                  | 0.4 ± 0.1                            | 1.9 ± 0.1                                      | 4.4 ± 0.8                                      |
| Skin                   | 0.9 ± 0.6                            | 4.0 ± 0.6                                      | 7.5 ± 1.4                                      |
| Thyroid                | 0.6 ± 0.1                            | 2.7 ± 0.1                                      | 5.1 ± 0.9                                      |
| Oesophagus             | 0.6 ± 0.2                            | 2.5 ± 0.2                                      | 5.3 ± 1.0                                      |
| Red Bone Marrow        | 0.5 ± 0.2                            | 2.3 ± 0.2                                      | 4.0 ± 0.7                                      |
| Lung                   | 0.6 ± 0.2                            | 2.8 ± 0.2                                      | 5.5 ± 1.0                                      |
| Liver                  | 0.7 ± 0.0                            | 3.3 ± 0.0                                      | 7.6 ± 1.4                                      |
| Bone Surface           | 0.5 ± 0.2                            | 2.1 ± 0.2                                      | 4.9 ± 0.9                                      |
| Stomach                | 0.7 ± 0.2                            | 3.2 ± 0.2                                      | 6.4 ± 1.2                                      |
| Colon                  | 1.0 ± 0.1                            | 4.4 ± 0.1                                      | 7.4 ± 1.4                                      |
| Ovaries                | 0.8 ± 0.1                            | 3.4 ± 0.1                                      | 7.4 ± 1.4                                      |
| Testes                 | 1.5 ± 1.0                            | 6.6 ± 1.0                                      | 17.6 ± 3.2                                     |
| Bladder                | 1.0 ± 0.1                            | 4.2 ± 0.1                                      | 8.6 ± 1.6                                      |
| Breast                 | 0.7 ± 0.2                            | 3.0 ± 0.2                                      | 7.2 ± 1.4                                      |

3.3 PET effective dose

For this study, average $^{18}$F-FDG activity injected to the patient is only $211.63 ± 51.2$ MBq. The activity is much lower compared to the $^{18}$F-FDG activity used in Huang et al. (2009) and Avamora et al. (2015) which is $370$ MBq [1, 3]. The mean effective dose for PET for this study is $4.02 ± 0.97$ mSv.

3.4 PET/CT effective dose

The average effective dose for the combined whole body PET/CT examination at our centre was found to be $14.82 ± 4.0$ mSv for DLP method and $9.47 ± 2.1$ mSv for SSDE method. Comparison of total PET/CT effective dose from previous study shown in Table 3. Our study showed lower effective dose from PET scan compare to the other studies because of the lower activity used. Our patients was injected based on their body weight following $3.5$ MBqkg$^{-1}$ standard which is $211.63$ MBq in average compare to Huang et al. and Avamora et al. (370 MBq). Meanwhile Willowson et al. used mean activity of $304$ MBq. However, radiation dose from the CT component were higher for the DLP method.

From this study, there is 49.5% difference in effective dose for the CT component, based on the two different methods. CT contributed as much as 58% (SSDE-based) or 73% (DLP-based) of the total effective dose for a whole body PET/CT examination. While noting that effective dose is a measure of the mean radiation burden based on a population, and not a measure of the radiation burden of an individual patient, it is nevertheless important to size the radiation burden to the population average man-size. Using the nominal risk coefficient for detrimented–adjusted cancer for adult of 4.0% per Sv, the lifetime cancer risk due to a whole body PET/CT examination is estimated to be 0.058% and 0.042% based on DLP and SSDE method, respectively [6]. This translates to an excess of 58 (for DLP based estimates) and 42 (for SSDE based estimates) solid cancer cases if a population of 100 000 adults received this amount of radiation dose.
Table 3. Study comparison

| Study                | Scan extension           | Activity | PET    | CT     | PET/CT  |
|----------------------|--------------------------|----------|--------|--------|---------|
| Huang et al. [1]     | base of scull to upper thighs | 370 MBq  | 6.23 mSv | 7.32 mSv | 13.55 mSv |
| Willowson et al. [2] | base of scull to mid-thighs | 304 MBq  | 6.30 mSv | 8.20 mSv | 14.50 mSv |
| Avamora et al. [3]   | head to feet             | 370 MBq  | 4.90 mSv | 8.90 mSv | 13.80 mSv |
| This study (DLP based)| base of skull to upper thigh | 212 Mbq   | 4.02 mSv | 10.8 mSv | 14.82 mSv |
| This study (SSDE based)| base of skull to upper thigh | 211.63 Mbq | 4.02 mSv | 5.45 mSv | 9.47 mSv |

4. Conclusion

Estimation of effective dose based on the simple DLP and SSDE methods was carried out and compared. The SSDE based effective dose was derived via empirical organ dose measurements in an anthropomorphic phantom. Patient specific effective dose for 104 patients were calculated and compared. DLP based method overestimated patient specific effective dose by a factor of 1.4 due to the smaller size of average Malaysian population. Hence, we recommended the use of SSDE method for more accurate effective dose and risk estimates for the Malaysian population.

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