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Patient Effective Dose Estimates in 18F-FDG PET/CT Studies using OLINDA/EXM and DLP Method

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Abstract: ***Positron emission tomography/computed tomography (PET/CT) is the standard of care in oncologic diagnosis and staging, and patient radiation dose must be well understood. The aim of this study is to determine the specific patient effective dose in 127 patients (80 male and 47 female) with an age range of 29–90 year from a PET/CT scan using 18F-FDG.PET dose was calculated by modifying the standard reference phantoms in OLINDA/EXM software with patient-specific mass. CT dose was calculated using a computationally simpler method based on the dose length product (DLP) and k factors. And found that the mean patient effective dose from a mean injected 18F-FDG activity of 179.04 ±46.75 MBq was 2.82 ± 0.47 mSv while the mean effective dose from the CT was 8.28 ± 3.46 mSv in all patients. The five organs receiving the highest equivalent dose from 18F-FDG, in order of highest to lowest dose, were urinary bladder, heart, brain and prostate (male)/uterus (female). The results show that the effective dose is significantly lower than other studies according to lower injected activity. Radiation dosimetry using patient-specific data into dose estimates is a worthwhile effort for characterizing patient dose, and the specific dosimetric information assists in the justification of risk and optimization of PET/CT acquisition parameters.***

Keywords: Radiation dosimetry PET/CT , 18F-FDG, Effective dose

1. Introduction

Positron emission tomography/ computed tomography (PET/CT) has become established prominently in clinical oncology as well as in all fields of diagnosis, staging, and treatment. PET/CT is a unique combination of the cross-sectional anatomic information provided by CT and the metabolic information provided by PET, which is acquired during a single examination and fused. The sequential acquisition of PET and CT images using 18F-Fluorodeoxy glucose (18F-FDG) PET/CT results in patient radiation dose from both imaging modalities. The risk incurred from this radiation dose is generally thought to be justified and optimized by the benefit of the diagnostic information obtained from the scan while maintaining radiation doses as low as reasonably achievable as a general principle of radiological protection according to the International Committee on Radiological Protection (ICRP) (1, 2). The effective dose is a quantity that attributes weighting factors to organs or tissues, representing the fraction of the total stochastic risk resulting from the irradiation of that organ or tissue (3). The effective dose is the value for comparing doses from different diagnostic procedures and for comparing the use of similar technologies and procedures in different hospitals and countries as well as the use of different technologies for the same medical examination. The use of the effective dose allows exposures in internal and external exposure to be combined in a single value (1). In PET/CT exams, the patient effective dose from PET and the patient effective dose from CT are first estimated separately in different ways and then combined to give a total body radiation dose.

The medical internal radiation dose (MIRD) schema is the most widely accepted formalism for PET/CT internal dose calculations. The absorbed dose is calculated to a certain region, called the target region, from activity in a source region as the product between the time-integrated activity and the S value (absorbed dose per decay) (4).The virtue of the MIRD approach is that it systematically reduces complex dosimetric analyses to methods that are relatively simple to use, including software tools for experimental and clinical use. The uncertainty in the dose estimate for an organ or tissue in a reference person reflects uncertainties in the cumulated activity and the S-value. The variation in mass of the target organ and, in the distance between the source and target organs are the major contributors to the uncertainty in S-values so the uncertainty for the dose to the reference person would be considerably lower than actual patient. The variation in the uptake and distribution of the radio pharmaceutical among the organs and tissues is often the major contributor to uncertainties in cumulated activity. The combined uncertainties in most radio pharmaceutical dose estimates will be typically at least a factor of two. Calculations have shown that estimates of effective dose to different organs will not generally deviate from actual effective dose in patients by more than a factor of two (5).

The representative indicators of radiation dose in CT are the volume CT dose index ($CTDI_{vol}$) and dose length product (DLP), a product of $CTDI_{vol}$ and scan length, and are provided on a PET/CT scanner automatically. $CTDI_{vol}$ is calculated on the basis of radiation dose measured in imaging 16 and 32cm CT dosimetry phantoms for head and body mode imaging, respectively.

$CTDI_{vol}$ is a useful indicator of the dose to a standardized phantom for a specific exam protocol because it takes into account protocol specific information. Common methods used to estimate effective dose for a CT examination include method based on organ dose estimates and the computationally simpler method based on the DLP and aDLP to effective dose conversion coefficient, referred to ask factors (6, 7).

Furthermore, specific values of effective dose can be calculated using several different software packages, which are based on the use of data from the National Radiological Protection Board (NRPB) in the United Kingdom and the Institute of Radiation Protection (GSF) in the Germany. The k factors are derived from calculations in which computational human phantoms are coupled with the Monte Carlo transport simulation of CT X-ray beams and depends on the location, size, and radio sensitivity of organs and tissues exposed to radiation. The k-factors were initially developed by Shrimpton et al (8) and subsequently, modified in the European Guidelines on Quality Criteria in Computed Tomography (EGs) (9). The k-factors for extended scan regions were published in the updated EGs (10), which was adopted in the American Association of Physicists in Medicine (AAPM) Report 96 and based on the tissue weighting factors published in the ICRP Publication 60. The values of effective dose predicted by DLP and the values of effective dose estimated using more rigorous calculations methods are remarkably consistent, with a maximum deviation from the mean of approximately 10% to 15%. Hence, the use of DLP to estimate effective dose appears to be a reasonably robust method for estimating (6).

The effective dose from PET is estimated based on the injected activity and patient size while the effective dose from CT is estimated based on scanner-specific parameter reported in the exam dose report. Both approaches can be made to be more accurate, reflecting the actual patient dose by including scanner and patient specific factors. The dependency of total dose on many factors warrants a critical review of general reference values and suggests the importance of specific data. Without specific information, risk evaluations may be based on reference or literature values that must be carefully chosen if used for risk evaluation.

The aim of the present study was to characterize the radiation dosimetry of PET/CT exams using commonly available dose estimation techniques and ascertain the utility of such results in the evaluation of risk/ benefit for justification and protocol optimization in routine clinical utilization.

2. Material and Method

The effective dose was estimated for 18F-FDG PET/CT examinations performed in 127 adult oncology patients over two a year period in Kuwait cancer control center. The patients were scanned using a GE Discovery 710 PET/CT, the CT portion comprised of a GE Light speed VCTCT unit. All patients received an intravenous injection of 0.06mCi/Kg of 18F-FDG. After an initial uptake phase of an approximately 60 minutes, a CT-Scan without oral or IV contrast, without breath holding at low mA level was acquired for attenuation correction and localization purposes only. Subsequently, PET images from vertex to mid-thigh were obtained using 2.0min/bed acquisition (6 to 10 bed positions in total).A scout scan was performed at 10mA prior to a CT scan for gross anatomical visualization. For each PET/CT exam, the following patient specific information was recorded from the patient medical record and CT dose monitoring software: Age (Years)at scan time, Gender, Height (cm), Body mass (kg), Body mass index (BMI), Administered activity (MBq), $CTDI_{vol}$ (mGy) and DLP(mGy.cm).

Olinda/ Exm Version 2.2 (Vanderbilt University) was used to calculate the PET organ equivalent dose and effective dose according to the MIRD technique. The program requires specification of the radio nuclide, organ residence time (Bq.hr/Bq), and anatomical phantom. The program offers the choice of twenty-five human and ten animal (rodent) phantoms. In the current study ICRP 89, adult male and female phantoms are selected. The biokinetic model parameters as defined in ICRP Publication 128 (11) for 18F-FDG were used as input factors for the program. The ICRP 128 bio- kinetic model for 18F-FDG was derived from data in Hayes et al (12) and Deloar et al (13). Phantom organ masses were scaled in the program by the ratio of the patient mass to the phantom mass. For electron emission, these results in a linear scaling of dose calculations with mass and for photons vary directly with the cube root of the mass (14).

The program then produced dose factors for each organ, in terms of equivalent dose and effective dose per unit-injected activity (mSv/MBq).The dose factors were multiplied by the injected activity to obtain the total equivalent dose for each defined organ and the total effective dose. The tissue weighting factors from ICRP Publication 103 were used to generate the effective dose conversion factor (mSv/MBq). While the program produced factors of equivalent dose as mSv, and due to the fact that 1mSv is equal to1 mGy for the radio nuclides with only photon or electron emissions, organ radiation absorbed dose is reported in Table 1 as mGy unit (11). Olinda/Exm reported dose factors for left colon, right colon and rectum and were port total colon PET dose as the average of the three.

The effective dose from CT examination was estimated using computationally simpler method based on the DLP and k factors as follows:

$$Effective\ dose\ = k \times DLP$$

Where the k coefficient is specific only to the anatomic region scanned. The k-factors used in current study were published in the EGs (9), and adopted in the American Association of Physicists in Medicine (AAPM) Report 96 (6).

DLP represent radiation exposure to the entires can length and was extracted form CT dose report:

$$DLP\ =\ CTDIvol\ \times\ Scan\ length$$

In this study the descriptive and summary statistics analysis were performed with Microsoft Excel 2016MSO (Version 2210 Build16.0.15726.20068). The statistical analysis included average, median, standard deviation, minimum, maximum and range.

3. Results

In this study, of the total 127 PET/CT scans evaluated, 80 (63 %) were performed on male patients and 47 (37 %) were performed on female patients. Subjects ranged in age from

29 to 90 years (mean ± standard deviation (SD) 57.59 ± 12.62 years). The subjects' weight ranged (mean ± SD) from 43.0 to 135 kg (76.32 ± 18.04 kg), height ranged (mean ± SD) from 138 to 187 cm (163.29 ± 10.32 cm), and BMI ranged (mean ± SD) from 18.13 to 54.77 (28.62 ± 6.46). The mean ± SD (range) 18F-FDG injected activity for all patients was 179.04± 46.75 MBq (97.31 to 351.87 MBq).

Radiation doses 18F FDG:
The five organs with the highest organ equivalent doses from 18F-FDG calculated by Olinda/Exm in all patients, in order of highest to lowest dose, were urinary bladder, heart, brain, and prostate (male patients)/uterus (Female patients).18F-FDG organ equivalent doses are summarized in Table 1.The mean ± SD (range) patient-specific effective dose from 18F-FDG for all patients was 2.82 ± 0.47 mSv (1.62 to 5.17 mSv), 2.71 ± 0.41 mSv (1.62 to 5.15 mSv) for male and 2.99 ±0.50 mSv (2.76 to 4.81mSv) for female. The mean±SD (range) effective dose per unit injected activity for all patients was 0.0162 ± 0.0044 mSv/MBq (0.0098 to 0.0030 mSv/MBq). 18F-FDG patient-specific effective doses are summarized in Table 2.

Radiation doses CT:
The mean ± SD (range) effective dose for all patients from the CT was 8.28 ± 3.46 mSv (2.36 to 16.98 mSv). The mean ± SD (range) dose length product (DLP) from all exams was 457.45 ±190.99 mGy-cm (130 to 937.97mGy-cm) for all patients. CT radiation doses are summarized in Table 3.

Total radiation doses PET and CT:
The mean ± SD (range) effective dose from the combined PET and CT of all PET/CT exams was 11.10 ± 3.50 mSv (3.50 to 19.54 mSv) for all patients, 11.14±3.54 mSv (6.20 to 19.54 mSv) for male patients and 11.04 ± 3.47 mSv (5.68 to 18.73 mSv) for female patients. The combined PET and CT effective dose are summarized in Table 4.

Table 1: Organ equivalent dose from 18F-FDG PET/CT to adult male and female patients calculated by Olinda

Equivalent dose (mGy) calculated by Olinda		
Organ	Male (n =80)	Female(n=47)
Adrenals	2.10±0.33	2.20±0.37
Brain	6.08±0.95	5.76±0.97
Breast	-	1.47±0.25
Esophagus	2.17±0.34	2.24±0.38
Eyes	1.76±0.28	1.88±0.32
Gallbladder Wall	2.39±0.37	2.08±0.35
Colon	2.20±0.34	2.69±0.45
Small Intestine	2.08±0.33	2.01±0.34
Stomach Wall	2.12±0.33	2.01±0.34
Heart Wall	10.83±1.69	11.95±2.01
Kidneys	1.83±0.29	1.89±0.32
Liver	3.74±0.59	3.94±0.66
Lungs	3.01±0.47	3.22±0.54
Pancreas	2.15±0.34	2.20±0.37
Salivary Glands	1.95±0.30	1.88±0.32
Red Marrow	1.78±0.28	1.79±0.30
Osteogenic Cells	1.79±0.28	1.73±0.29
Spleen	1.73±0.27	1.83±0.31
Testes/ Ovaries [a]	1.74±27	2.65±0.44
Thymus	2.27±0.36	2.30±0.39
Thyroid	1.73±0.27	1.67±0.28
Urinary Bladder Wall	23.24±03.63	22.71±3.81
Prostate/Uterus [b]	3.11±0.49	3.77±0.63
Total Body	1.86±0.29	2.05±0.34
Effective dose	2.72±0.41	2.99±0.50

[a]Testes for male patients Ovaries for female patients
[b]Prostate for male patients Uterus for female patients

Table 2: 18F-FDG effective Dose summary

Injection activity (MBq)		Effective dose per unit activity (mSv/MBq)		Effective dose (mSv)	
Male	Female	Male	Female	Male	Female
180.44 ±45.96	176.66 ±48.48	0.016±0.004	0.018±0.004	2.72±0.41	2.99±0.50

Table 3: CT effective dose summary

CTDI $_{Vol}$ (mGy)		DLP (mGy.cm)		Effective dose (mSv)	
Male	Female	Male	Female	Male	Female
4.76±2.36	4.88±2.66	464.94±190.02	444.70±194.02	8.42 ±3.44	8.05±3.51

Table 4: Effective dose for male and female patients

18F-FDG and CT		CT		Total	
Male	Female	Male	Female	Male	Female
2.72±0.41	2.99±0.50	8.42 ±3.44	8.05±3.51	11.14±3.54	11.04±3.47

4. Discussion

A reliable method of managing patient dose, which includes appropriate calculation methods, is important for PET/CT exams. Methods that incorporate exam-specific parameters require considerable effort to collect and appropriately analyze data but provide results that more accurately represent the individual patient than generalized methods. The methods employed in this study resulted in organ equivalent doses and effective doses that are in agreement with published data (Table 5). Accurate estimation of the patient dose is important for oncology patients who are likely to receive multiple scans over the course of their disease management. In the current study, the 127 PET/CT examinations for which dosimetry was performed represent 37 unique patients, indicating that patients often underwent multiple scans.

The Olinda/ExamVersion 2.2 used in this study represents many improvements over the previous version, which serves to increase the accuracy of individual patient dosimetry. The software allows calculations for over 1000 radio nuclides and employs the latest phantoms of both genders, which are neither voxelized nor stylized, but are anatomically realistic and can easily be modified for more patient-specific dose calculations. The modification of the phantom organ results in a linear scaling of dose calculations with mass for electron emission and varies directly with the cube root of the mass for photons.

The scaling of phantom organ mass in Olinda 2.2 made

phantoms more representative of individual patient body size than the default phantom, but still not as specific to the patient as would be from the segmentation of an actual patient image. Comparing effective dose values estimated by DLP method used in this study for a wide range of scanner models with effective dose values derived from NRPB organ dose calculations and ICRP 60 tissue weighting factors, alinear relationship was found (15), when data sets were restricted to the same anatomic region. Further deviations in estimates of effective dose of ±15% have been reported using DLP method relative to thegold standard organ dose method (6).

In light of the wide range of considerations for accurate dosimetry, including patient size, age, and imaging technique, a variety of dosimetry methodologies including those examined in the current study are beneficial to have on hand.

Table 5: Comparison of results with reference and literature

	IAEA RPOP[b]	Literature[c]	This study
Injected activity (MBq)	400	454	179.04
Effective dose PET (mSv)	8	9	2.82
Effective dose CT(mSv)[a]	7	5	8.28
Total effective dose PET/CT (mSv)	15	15.4	11.10

[a]CT technique for attenuation correction only
[b] International Atomic Energy Agency, Radiation Protection of Patients
[c] Quinn et al. BMC Medical Imaging (2)

5. Conclusions

The effective dose estimates, is important to understanding how radiation dose relates to patient detriment and is essentials for a strict benefit analysis applicable to any medical imaging modality. Routine evaluation of individual patient dose is a key component in improving understanding of the relationship between radiation exposure and associated risk. Appropriated dosimetry methods such as those in the current study facilitate a meaningful understanding of patient radiation dose by accounting for dosimetry factors representative of the patient and exposure scenario.

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