Evaluation of patient absorbed dose in a PET-CT test

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Abstract

Images of PET-CT has important diagnostic applications, especially in oncology. This equipment allows overlapping of functional images obtained from the administration of radionuclides and anatomical, generated by x-rays. The PET-CT technique may generate higher doses in patients due to the fact that two diagnostic modalities are used in a single examination. A whole body CT scan is performed and in sequence, a capture of the signal generated by the photons emitted is done. In this study, the absorbed and effective doses generated by the CT scan and incorporated by the administration of the radionuclide were evaluated in 19 organs. To evaluate the CT dose, 32 radiochromic film strips were correctly positioned into the anthropomorphic male phantom. The CT protocol performed was whole-body scanning and a high-resolution lung scan. This protocol is currently used in most services. The calculation of the effective dose from the injected activity in the patient was performed using the ICRP 106 Biokinetic model [ICRP 106, 2008]. The activity to be injected may vary according to the patient's body mass and with the sensitivity of the detector. The mass of the simulator used is 73.5 kg, then the simulation with an injected activity of 244.76 MBq was used. It was observed that 87.4% of the effective dose in examination PET/CT comes from the CT scans, being 63.8% of the whole body scan and 23.6% of high-resolution lung scan. Using activity of 0.09 mCi x kg ^{18}F-FDG radiopharmaceutical contributes only 12.6% of the final effective dose. As a conclusion, it was observed that the dose in patients submitted to the ^{18}F-FDG PET-CT examination is high, being of great value efforts for its reduction, such as the use of appropriate image acquisition techniques and promoting the application of the principle of optimization of practice.

Keywords: Computed Tomography, PET-CT test, dosimetry.

1.- INTRODUCTION

Since its introduction, the combination of Positron Emission Tomography (PET) and Computed Tomography (CT), or PET/CT, has received great attention in the medical community. These compound tomographic devices allow the overlapping of functional images obtained from the administration of radiopharmaceuticals and anatomical images generated by X-ray beam attenuation.

The clinical applications of PET/CT have been expanding, mainly in oncologic diagnosis and management, but also for other clinical indications, leading to the increasing demand for PET/CT studies and more combined PET/CT scanners being installed in hospitals and clinics around the world. However, PET/CT examinations, especially those that include diagnostic CT, result in increased patient radiation exposure compared with a single CT or PET examinations, as the effective dose is a combination of the dose from PET and the dose from CT [HUANG, 2009].

1.1.- Theoretical basis

The principle of PET technology is based on the coincident detection of two 511 keV gamma photons emitted from the decay of a positron-emitting radionuclide injected into the patient, when occurs an electron-positron annihilation. Fludeoxyglucose (^{18}F-FDG), a glucose analog, is a tracer of positron-emitting cell metabolism, non-invasively registered by PET, and is currently the most widely used for image production. Photon detection is done by the PET acquisition system, detectors that convert the high energies of the detected photons into electrical signals, treated by mathematical algorithms to obtain PET image. This conversion efficiency is known as sensitivity, the number of counts per unit of time detected by the device, per unit of activity of source and depends on the geometrical characteristics of the system and detection mode, i.e., it can be different for each equipment [Robilotta, 2006].

A number of photons produced is proportional to the quantity of radiopharmaceutical activity administered to the patient. The photons that emerge from the patient are captured externally by a set of scintillator detectors in a circular arrangement [Robilotta, 2006]. The amount of activity injected varies according to the patient mass and with the detector sensitivity [ICRP 106, 2008].

Several studies have been carried out by nuclear medicine societies and their collaborators, trying to standardize protocols for the acquisition and interpretation of PET/CT examinations with ^{18}F-FDG. However, the guidelines indicate for the calculation of the activity, only weight and age variables, separated for adults and children, without considering or qualifying parameters of image quality related to the equipment.

The objective of this work was the evaluation of the final Effective Dose (E), considering the dose from CT scan and according to the activity of the radiopharmaceutical injected into the patient. The Alderson Rando® male phantom was used to assess the Absorbed Dose (D_T) from CT scan. It consists of a human skeleton wrapped in a polymeric material with equivalent tissue characteristics [OLIVEIRA, 2013]. The activity of ^{18}F-FDG to be injected may vary according to the patient mass and the detector sensitivity. The effective dose was evaluated using the model proposed by the International Commission on Radiological Protection (ICRP) number 106, entitled "Radiation Dose to Patients from Radiopharmaceuticals biokinetic model" [ICRP 106, 2008].

2.- MATERIALS AND METHODS

The experiments were performed in the PET/CT in Molecular Medicine Technology Center (CTMM) at Federal University of Minas Gerais (UFMG). This imaging center is equipped with a PET/CT Discovery 690 (D-690) from the General Electric (GE) manufacturer.

To evaluate the absorbed doses from the CT scan, the Alderson Rando male model phantom was used. It consists of a human skeleton wrapped in a polymeric material with equivalent

tissue characteristics, with the trunk and the head sliced in thicknesses of 2.5 cm, a total of 33 slices. In these slices, 7 mm diameter cylinders are uniformly arranged for the positioning of radiation detectors, in 5794 internal points for possible dose evaluation [OLIVEIRA, 2013].

Radiochromic films strips were placed inside the phantom at points corresponding to the following organs: brain, crystalline, hypophysis, bone marrow, thyroid, lung, heart, breast, liver, spleen, gallbladder, stomach, pancreas, small intestine, colon, kidneys, sigmoid, bladder, and testicles. A strip was reserved to be used as Background (BG) radiation reference and was left outside the examination room.

The phantom position into PET/CT table is shown in Figure 1. A scout was performed along a distance of 150 cm from the patient on the skull-caudal axis, using 120 kV, 10 mA and tube rotation time of 1 s, sweeping from the top of the head until the root of the thigh.

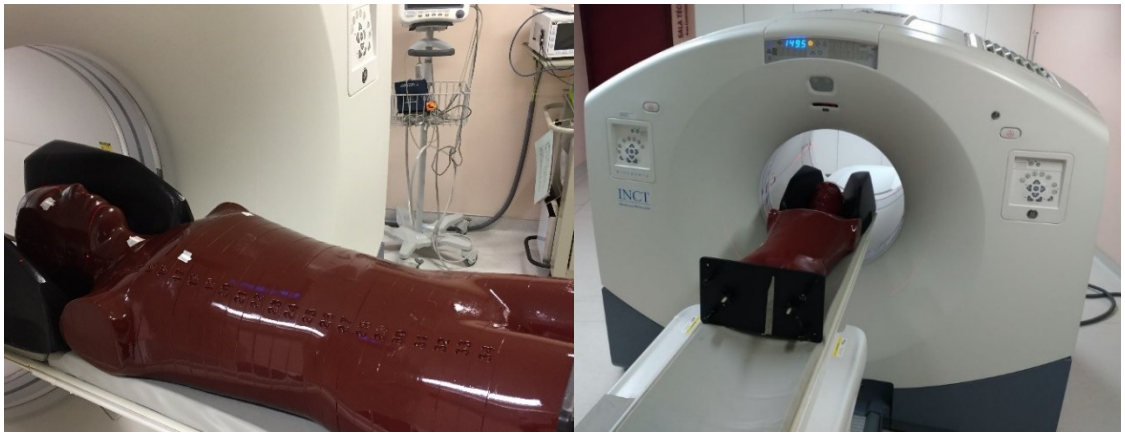

Figure 1. –Alderson phantom positioned into the PET/CT scanner

The tomographic protocol was performed in two parts, a full body scan, and a High Resolution (HR) lung scan. This second protocol is commonly used for lung diagnostic function. A day after CT scan, the film strips were scanned and for generate their digital images and obtain the absorbed dose values in the organs. The calculation of the absorbed dose point was performed according to the calibration curve for 120 kV.

For the calculation of the effective dose from the injected activity into the patient, the biokinetic model of ICRP 106 was used. This activity varies according to the patient's body mass and the sensitivity of the detector. The phantom mass is 73.5 kg, and the protocol used was 3.33 $MBq.kg^{-1}$, therefore, the injected activity was 244.76 MBq.

2.1.- CT scan Dose Calculation

Two CT scans were performed, initially the whole-body scan and a high-resolution lung scan. The parameters used are shown in Table 1.

Table 1. – Parameters used in the Whole Body scan protocol

Parameter	Scan type	
	Whole Body	**Lung HR**
Reconstruction (mm)	3.75	5.00
Pitch	0.984	0.984
Tube time (s)	0.7	0.7
Voltage (kV)	120	120
Current (mA)	Auto	Auto
Smart mA	Active with AEC*	Active
mA range	50-400	50-400
Noise Index	16.05	15.04

*Automatic Exposure Control (AEC)

In the lung scan, only the area corresponding to lung tissue was irradiated, as shown in Figure 2, but the strips were inserted throughout the phantom, aiming the evaluation of scattered radiation dose.

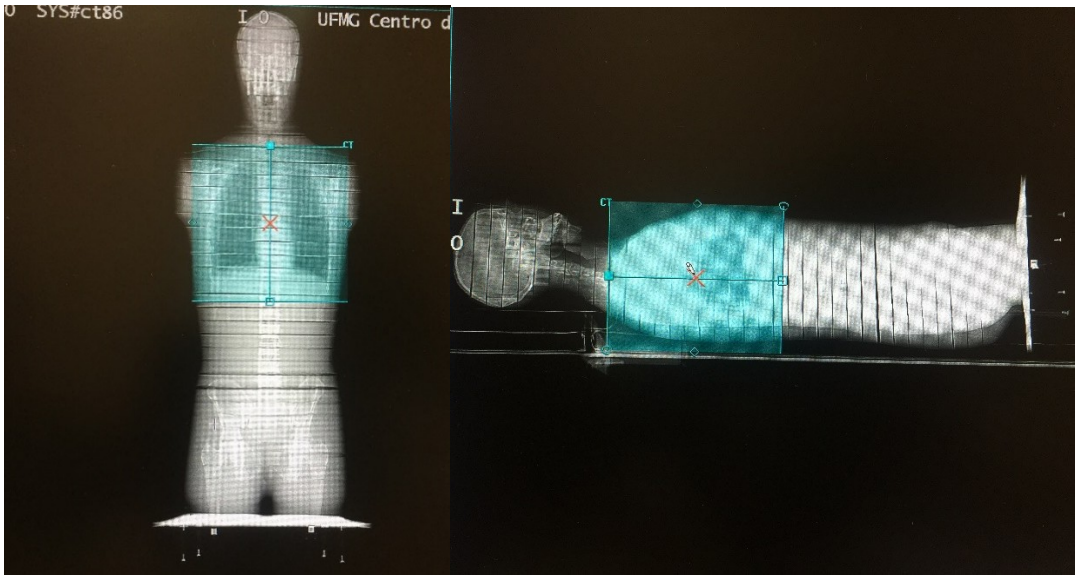

Figure 2. – Irradiated area in the HR Lung protocol.

After scans, the film strips were scanned with an output resolution of 300 ppi. The images were analyzed using the image processing software *"ImageJ"*. To obtain the BG and organ doses, equation 1 was used for change the intensity of the film strip darkness in absorbed dose.

[redacted] (1)

The mean and standard deviation of the absorbed dose values were calculated, thus obtaining the value for each measure point.

The absorbed dose is not sufficient to estimate the risk caused by a given radiation exposure since the effects of ionizing radiation do not depend solely on this magnitude.

The Effective Dose (E) is a magnitude that considers besides the absorbed dose (D_T), the weight factor related to tissue radiosensitivity (W_T), as well as the type of incident radiation (W_R), according to Equation 2 [ICRP, 1979].

[redacted] (2)

W_T values are shown in Table 2.

Table 2.- Tissue weighting factors according to ICRP 103

Tissue	W_T
Bone-marrow (red), colon, lung, stomach, breast, remaining tissues(*)	0.12
Gonads	0.08
Bladder, esophagus, liver, thyroid	0.04
Bone surface, brain, salivary glands, skin	0.01

*Remaining tissues: Adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

ICRP 103, 2007

2.2. – ^{18}F-FDG Dose Calculation

According to the model proposed by ICRP 106, coefficients ($\Gamma_T^{18F-FDG}$) are used that can calculate the amount of absorbed dose in the organs (D_T) from the radioactive Activity (A) injected and thus determine the Effective Dose (E) to the patient. Using the tissue or organ-weighting factor (W_T), the radiation type weighting factor (W_R), the quantity of injected radionuclide (^{18}F) and the patient age, according to Equations 2 and 3 [ICRP 106, 2008]

[redacted] (3)

The coefficient ($\Gamma_T^{18F-FDG}$) for each organ are presented in the follow table.

Table 3.- Absorbed dose per unit activity administered (mGy/MBq)

Organ	$\Gamma_T^{18F-FDG}$ (mGy/MBq)
Adrenals	1.2E-02
Bladder	1.3E-01
Bone surfaces	1.1E-02
Brain	3.8E-02
Breasts	8.8E-03
Gallbladder	1.3E-02
Gastrointestinal tract	
Stomach	1.1E-02
Small intestine	1.2E-02
Colon	1.3E-02

Upper large intestine	1.2E-02
Lower large intestine	1.4E-02
Heart	6.7E-02
Kidneys	1.7E-02
Liver	2.1E-02
Lungs	2.0E-02
Muscles	1.0E-02
Oesophagus	1.2E-02
Ovaries	1.4E-02
Pancreas	1.3E-02
Red marrow	1.1E-02
Skin	7.8E-03
Spleen	1.1E-02
Testes	1.1E-02
Thymus	1.2E-02
Thyroid	1.0E-02
Uterus	1.8E-02
Remaining organs	1.2E-02
Effective dose (mSv/MBq)	1.9E-02

ICRP 106, 2008

The amount of simulated activity was 3.33 MBq (0.09 mCi). The value of activity was multiplied by the Alderson phantom mass, of 73.5 Kg. The total of injected activity was 244.76 MBq. It was multiplied by the coefficient ($\Gamma_T^{18F-FDG}$) and the effective dose was found.

3. - RESULTS

3.1. – CT Scan Dose

The results of Absorbed Dose and Effective Dose, as well as the associated uncertainties for the high-resolution lung and whole body scans, are presented in Table 4.

Table 4.- Absorbed and Effective Dose in CT scan

Organ	Whole Body Scan				Lung HR	
	W_R	W_T	D_T [mGy]	E [mSv]	D_T [mGy]	E [mSv]
Brain	1	0.01	5.54 ± 0.57	0.06	0.00 ± 0.00	0.00
Crystalline	1	0.01	9.85 ± 0.66	0.13	0.00 ± 0.00	0.00
Hypophysis	1	0.01	3.81 ± 0.57	0.05	0.00 ± 0.00	0.00
Bone Marrow	1	0.12	11.21 ± 0.38	1.35	0.92 ± 0.25	0.11

Thyroid	1	0.04	41.07 ± 0.81	1.64	34.96 ± 0.44	1.40
Lung	1	0.12	20.58 ± 0.78	2.47	12.59 ± 0.44	1.51
Hearth	1	0.01	20.61 ± 0.75	0.27	13.20 ± 0.42	0.18
Breast	1	0.12	24.30 ± 1.08	2.92	15.08 ± 0.53	1.81
Liver	1	0.04	19.21 ± 1.08	0.77	11.35 ± 0.35	0.57
Spleen	1	0.01	14.23 ± 0.76	0.19	9.92 ± 0.39	0.13
Gallbladder	1	0.01	20.86 ± 0.64	0.28	9.19 ± 0.54	0.12
Stomach	1	0.12	20.02 ± 1.01	2.40	8.21 ± 0.39	0.99
Pancreas	1	0.01	15.97 ± 1.36	0.21	3.36 ± 0.43	0.04
Small intestine	1	0.01	16.90 ± 0.95	0.23	3.33 ± 0.35	0.04
Colon	1	0.12	18.10 ± 0.72	2.17	3.27 ± 0.31	0.39
Kidney	1	0.01	15.81 ± 0.88	0.21	0.01 ± 0.18	0.00
Sigmoide	1	0.01	20.95 ± 0.70	0.28	0.00 ± 0.00	0.00
Bladder	1	0.04	31.53 ± 0.67	1.26	0.00 ± 0.00	0.00

Testicles	1	0.08	35.72 ± 1.00	2.86	0.00 ± 0.00	0.00
Total Effective Dose [mSv]				19.74		7.30

3.2. – ^{18}F-FDG Dose Calculation

The Effective Dose results found were calculated using equations 3 and 4 and are shown in Table 5.

Table 5. – Effective Dose from ^{18}F-FDG injection

Organ	**E [mSv]**
Brain	0.0930
Crystalline	0.0044
Hypophysis	0.0044
Bone Marrow	0.3231
Thyroid	0.0979
Lung	0.5874
Hearth	0.0044
Breast	0.3524
Liver	0.2056
Spleen	0.0044

Gallbladder	0.0044
Stomach	0.3231
Pancreas	0.0044
Small intestine	0.0044
Colon	0.3818
Kidney	0.0044
Sigmoid	0.0044
Bladder	1.2727
Testicles	0.2154
Total Effective Dose [mSv]	3.89

4.- DISCUSSION

The dose values vary considerably from one organ to another. In the whole body scan, the highest absorbed doses were found in the thyroid and testicles, with values of 41.07 and 35.72 mGy, respectively, however, when the effective dose is observed, breasts and testicles assume a higher value, with 2.92 and 2.86 mSv respectively.

In high-resolution lung scanning, some points showed very low dose value in relation to BG and were considered as zero. This is because only a part of the simulator has been irradiated, thus, these points received negligible doses when compared to the values of other organs. Thyroid, with 34.96 mGy and breasts, with 15.08 mGy presented higher absorbed dose. Considering the radiosensitivity of the tissues, breasts, and lungs received a higher effective dose, with 1.81 and 1.51 mSv respectively.

Analyzing the effective dose from the administration of ^{18}F-FDG, the bladder receives the highest value, 1.27 mSv, fact justified by the route of excretion of this radiopharmaceutical being mostly via the urinary tract.

Next, they appear lung, with 0.58 mSv and colon, with 0.38 mSv. The lowest values are found in the crystalline, hypophysis, heart, spleen, gallbladder, pancreas, small intestine, kidneys and sigmoid, each with a value of 0.0044 mSv. These organs are less radiosensitive and do not contribute so much to the effective dose.

Considering the whole exam, the organs that received the highest effective doses were: breasts with 5.08 mSv, lungs with 4.57 mSv and stomach with 3.71 mSv. The lowest effective doses were found in the hypophysis, crystalline, and brain, with 0.06, 0.14 and 0.15 mSv respectively.

5.- CONCLUSIONS

It was observed that 87.4% of the effective dose in PET/CT exam is produced by CT scans, being 63.8% of the whole body scan and 23.6% of the high-resolution lung scan. Using 0.09 mCi.kg, the ^{18}F-FDG radiopharmaceutical contributes only 12.6% of the final effective dose.

The importance of the optimization of the tomographic protocols is emphasized since CT is responsible for most of the final effective dose to the patient. Optimization and justification of practice are principles of radioprotection. Doses should be as low as reasonably achievable and yet, every procedure should bring benefits to the patient greater than the associated detriment. High-resolution lung scanning should be performed only on patients with oncologist indication, not as service protocol.

In addition, it should be noted the need for the activity injected into the patient be proportional to its body mass and the detector sensitivity, thus avoiding unnecessary exposure.

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