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Uncertainties in effective dose estimation for CT transmission scan in total body PET-CT imaging with Auto mA3D tube current modulation

Y. Salimi[1], M.R. Deevband[1*], P. Ghafarian[2, 3], M.R. Ay[4]

[1]*Department of Medical Engineering and Physics, Shahid Beheshti University of Medical Sciences, Tehran, Iran*
[2]*Chronic Respiratory Diseases Research Center, National Research Institute of Tuberculosis and Lung Diseases (NRITLD), Shahid Beheshti University of Medical Sciences, Tehran, Iran*
[3]*PET/CT and Cyclotron Center of Masih Daneshvari Hospital, Shahid Beheshti University of Medical Sciences, Tehran, Iran*
[4]*Research Center for Molecular and Cellular Imaging, and Department of Medical Physics and Biomedical Engineering, Tehran University of Medical Sciences, Tehran, Iran*

► ***Original article***

Corresponding authors:
M.R. Deevband, Ph.D.
***Fax:** +98 21 2243 9941*
E-mail:
mdeevband@sbmu.ac.ir

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ABSTRACT

Background: Positron Emission Tomography-Computed Tomography (PET-CT) is a useful hybrid imaging modality in the diagnosis of various malignancies. This modality imposes almost 20 mSv radiation dose to the patient. The purpose of the present study was to evaluate the uncertainties in calculated CT effective dose in TUBE CURRENT MODULATION-activated scans by Impact-Dose software. ***Materials and Methods***: Sixty total body DICOM (30 male and 30 female) whole body PET-CT images were selected. Volume CT Dose Index (CTDIvol) was recorded for each of the procedures. The image was divided into 5 regions of head & neck, chest, abdomen, pelvis and lower limbs according to special anatomical markers. Effective doses for total body and separate organs were calculated by means of Impact-Dose software once with global CTDIvol and once with a summation of doses calculated by 5 Regional CTDIvol and related scan ranges. ***Results:*** The difference among effective doses for some organs and total body were considerable. The mean and standard deviation (SD) of the coefficient of variations (CV%) for total body, breast, gonads, liver, lung, red bone marrow (RBM), thyroid, kidneys, and uterus were 12.56, 11.61, 9.44, 8.1, 11.31, 5.93, 8.61, 6.03 and 12.49, respectively. Uncertainties were higher for smaller patients by 19 noise indexes while these changes were higher for bigger patients and 22 noise indexes. ***Conclusion:*** The tube current variation depends on the acquisition and patient parameters. For measuring and reporting the total body and organs' effective doses in order to estimate the risks of CT's radiation for total body PET-CT procedures, the tube current variations must be considered.

Keywords: *Effective dose, computed tomography, individual dosimetry, PET-CT, regional CTDI.*

INTRODUCTION

Computed tomography (CT) is known as an important artificial source of public exposure [1, 2]. There are increasing concerns regarding hazardous effects of CT's radiation dose [3-5]. Information about the amount of radiation dose imposed to patients and public through a medical examination is a critical part in the realization of radiation protection rules, justification, and optimization. There are uncertainties in quantities for calculation and reporting of CT absorbed dose [6-10]; especially when the purpose is a comparison among different modalities. The most common and reachable dose quantities are $CTDI_{vol}$ and Dose

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Length Product (DLP) which are reported online and recorded on standard DICOM formats. The $CTDI_{vol}$ and DLP are incapable parameters to assess the risks of stochastic effects of radiation; they can be utilized just for comparing the dose for the same patient or scan situation [11]. The more useful quantity is an effective dose (ED), which is calculated by multiplying organ doses to their weighting factors based on stochastic effects[12]. There is a software to calculate effective dose for a specific acquisition and patient situations based on pre-tabulated Monte -Carlo simulation results [9, 13]. Impact-Dose is a user-friendly, fast and Monte-Carlo based software, which can calculate organs and effective doses for almost all of manufacturers and product models [9]. Nowadays, CT scan exposure parameters vary depending on its wide indications. An ongoing application of CT images is attenuation correction in fusion with functional Positron Emission Tomography (PET) and Single Photon Emission Competed Tomography (SPECT) systems. The CT image as a high-quality, noiseless and fast option is a critical and essential part of PET-CT hybrid imaging [14]. The importance of accurate measurement, calculation, and reporting of CT dose is increased by the fact that approximately, two-thirds of total dose in PET-CT examination are caused by CT scan [15]. The most common indication of PET-CT examination is diagnosis or treatment following patients with cancer; whole body and total body scanning, usually from base-skull to mid-thigh and from skull to toe, respectively are performed routinely [16]. Fortunately, by implementing TUBE CURRENT MODULATION techniques, the patient dose is reduced significantly compared with fixed tube current (FTC) mode [17]. CTDI is based on tube voltage (kVp) and averaged tube current (mA) in the whole of the scan. In fact, the CTDI is not constant for every part of the body; it is important to know the absorbed dose of organs with a different tissue weighting factor to calculate the more useful quantity of effective dose. The same study [18] evaluated the feasibility of using regional $CTDI_{vol}$ to calculate specific organ doses by using Monte-Carlo simulation for chest, abdomen and pelvic limited range diagnostic CTs by considering the regression with body diameter as a criterion of accuracy. The tube current modulation method which uses both angular and patient axis modulation is called Auto mA3D in General Electric (GE) PET-CT systems. The purpose of this study was to evaluate the precision of globally averaged $CTDI_{vol}$ in estimating total body and specific organs' effective doses in total body PET-CT scans by varying the acquisition parameter of Noise index (NI) and different patients, by Impact-dose software.

MATERIALS AND METHODS

Image acquisition

All of the images were taken by Discovery690 GE PET-CT manufactured in United States of America mounted in nuclear medicine Department of Masih Daneshvari Hospital, Tehran, Iran. A 64 slice VCT CT tube is assembled on this device. All the acquisitions were in arms-up position. The GE Auto mA3D technique was activated for all scans. The Pitch factor of 0.984 was chosen. The scan coverage was from the skull to mid-thigh. The CT console dose reports were based on the 32 cm phantom calibration for all scans. Data of 60 adult patients in two phases with GE AutomA3D TCM system (30 men and 30 women) were recorded. Thirty patients (15 men and 15 women) were scanned with 19 noise index and 30 patients (15 men and 15 women) with 22 noise index. Demographic information for patients is presented in table1. Patients with metal objects in the field of view and arm-down position were excluded.

Regional CTDI calculation

Total body PET-CT images were transported to a personal computer in DICOM format. The implemented tube current in each slice was extracted from DICOM header of images by MatLab software. Total body scans were segmented into 5 regions along the Z-axis which include lower limbs, pelvis, abdomen, chest and head & neck. The mean tube current for each part of the body was recorded. Then by equation

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1, regional $CTDI_{vol}$ was calculated for head & neck, chest, abdomen, pelvic, and lower limb regions. Then to investigate the effectiveness of Auto mA3D system in modulating the tube current, in each slice in Z-axis, the effective area of the patient body in the image was extracted by multiplying the patient area in the image by the average attenuation calculated by the CT numbers. The attenuation coefficient image was yielded by equation 2. The adeptness and changes of tube current and effective area was investigated in two noise indexes of 19 and 22. These calculations were done by MatLab software.

Equation 1[18]:

$$CTDIvol,Regional = CTDIvol,Global \times \frac{average\ regional\ tube\ current}{average\ global\ tube\ current}$$

$$DLP_{regional} = CTDIvol,Regional \times Region\ length$$

Where CTDI regional is the regional CTDI averaged over one part of body. And global CTDI is CTDI averaged over the total body.

Equation 2: $\mu 511Kev=\mu_w (0.001\times CT\ number+1)$.

Where μ511Kev is attenuation coefficient of object at PET 511 Kev energy and μ_w is the attenuation coefficient of water at energy of CT acquisition.

Effective dose estimation

Two approaches were compared to assess the patient effective dose, the global and regional $CTDI_{vol}$. Patient effective diameter as AAPM Report #204 was measured on axial CT images in abdomen region for all the patients as shown in figure 1 [19]. The total body effective dose and the dose of special sensitive organs of the breast (female), gonads, liver, lungs, thyroid, red bone marrow (RBM), kidneys and uterus (female) were measured. Impact-Dose version 2.3 software bought from GMBH Company, Germany was used to calculate the effective doses. The adult ORNL phantom available on software was used based on patient data (effective diameter) [20, 21]. The kVp, slice thickness, number of detector rows, pitch, scan coverage and $CTDI_{vol}$ were given to this software. Total coverage equal to coverage of CT acquisition was selected by normalizing the scan length with patient height and scan range (equation 3). The patient height was recorded in DICOM header of images. The length of the scan in patient craniocaudal (Z) direction was measured on sagittal images reconstructed in ImageJ software. The ratio of scan length to patient height was implemented on ORNL adult phantom. The start and end of scan ranges were fitted by anatomical markers on CT image and markers mentioned in Impact manual by a well-experienced radiologist. The output of Impact is total body effective dose and doses of organs indicated on the ICRP103 report.

equation3:

Impact Phantom lower limb range= Scan axial length measured on coronal image

$$\times \frac{Impact\ phantom\ height}{patient\ height}$$

Effective dose calculated by Global $CTDI_{vol}$

The kVp, slice thickness, number of detector rows 64*, pitch, scan coverage and $CTDI_{vol}$ were given to this software. Total coverage equal to coverage of CT acquisition was selected by normalizing the scan length with patient height and scan range (Equation 3). Global $CTDI_{vol}$ was entered as measured dose quantity, and TCM method was chosen. The effective dose and organ doses were recorded.

Effective dose calculated by Regional $CTDI_{vol}$

Then for the same patient, limited regional coverage which is shown in table 2, regional $CTDI_{vol}$ as the measured dose indicator and TCM mode was given to Impact-Dose software to calculate effective doses. Therefore, organ and effective dose were considered to be equal to the summation of regional values. An important note considered in adjacent fields is that: in multi-detector CTs due to over-ranging effect, the larger field than scan coverage is irradiated in the boundary of the field [22]. So for calculating the effective doses in several fields, 1-row detector scanner was considered for regional calculations. At the end, the effect of over-ranging on beginning and ending of scan

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length was compensated by calculating the effective dose once with one-row and once with a 64-row detector for total-body field and Global $CTDI_{vol}$.

Statistical analysis

The coefficient of variations was calculated by Equation 4[23]. Kolmogorov-Smirnov test was used to assess the normality of distributions. Independent samples *T-test* was used to compare male and female results. Paired sample T-test was used to compare doses calculated by two methods. Pearson and Spearman tests were used to find correlations. P-values <0.05 were considered statistically significant. SPSS IBM V18 was used for statistical analysis.

To compare the doses by two methods, the paired T-test was used. To compare the changes in two groups of 19 and 22 noise indexes, the independent t-test was used. Where, the COV is coefficient of variation.

Equation 4:

$$COV=\frac{(Effective\ Dose\ calculated\ by\ Regional\ approac)-(Effective\ Dose\ calculated\ by\ Global\ approach)}{Effective\ Dose\ calculated\ by\ Global\ approach}$$

Table 1. Demographic information of patients .

parameter	mean	SD	minimum	maximum
age	42.36	21.30	17	81
weight	72.55	16.47	47	112
Effective diameter	31.37	4.07	24.75	41.82

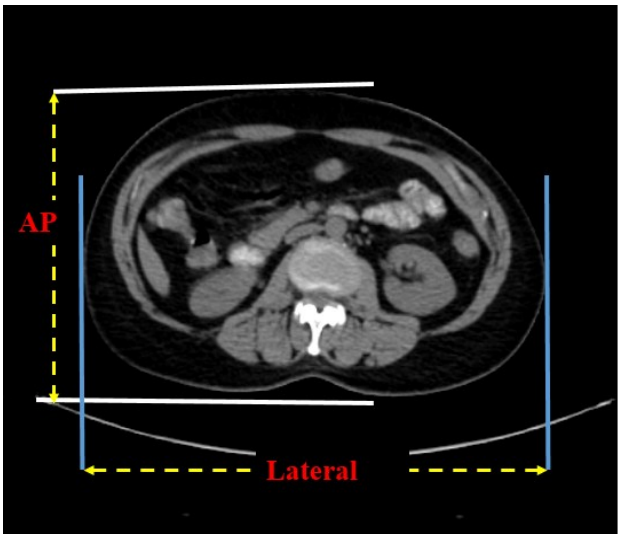


Figure 1. Measurement of AP and lateral diameter in patients.

Table 2. The 5 regions of body segments; the anatomical markers on axial images and the equivalent heights on Impact-Dose phantom for both of genders. (These markers were indicated according to Impact-Dose guideline).

Body region	Anatomical markers	Range on Impact Dose adult phantom	
		Female Phantom	Male Phantom
Head & neck	From apex of lungs up-to skull	0-30.6	0-31.4
Chest	From base of lungs to apex of lungs	30.6-50.8	31.40-55.2
Abdomen	From lowest part of liver to base of lungs	50.8-65.8	55.2-71.6
Pelvis	From symphysis pubis to lowest part of liver	65.8-90	71.6-98.6
Lower limbs	From feet up-to symphysis pubis.	90-168	98.6-179

RESULTS

Changes in ED calculated in patients

By Auto mA 3D system, the tube current and the regional $CTDI_{vol}$ was varied drastically during a patient total body scan (to 3 fold,). The average SD of regional $CTDI_{vol}$ for 5 regions was 1.17 mGy. The CV of total body and organ effective doses for both approaches are presented in table 3 for noise indexes of 19, 22. The total body effective doses calculated by summation of regional doses were significantly higher than global calculated dose in both NI groups (P<0.001).

The global averaged $CTDI_{vol}$ has produced underestimation of the total body effective dose

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for all of the cases (men and women). However, for specific organs which were assessed in this study, it either underestimates or overestimates the effective dose. These changes are shown in table 4. The most average absolute error was seen for thyroid gland for both genders (1.68 and 1.30_{mSv} for men and women, respectively). The significant correlations were seen among SD of regions' tube currents and effective doses for breast, lung and total body. The significant correlation was revealed between effective diameter and patient weight (P<00.1). The effective size of patients was calculated as 27.79±2.31 and 29.29±6.25 for men and women, respectively. There was no correlation between gender and CV of two methods neither for total body nor for specific organs common in men and women. Figure 2 and figure 3 shows the effective doses calculated by two methods for men and women, respectively. The SD of regional tube currents showed a direct significant relationship with CV of doses calculated by two methods (Pearson, P<0.05). In all of the cases with BMIs more than 25, the implemented tube currents reached the highest allowable amount defined by the operator. In cases with BMI, more than 35 of the tube current reached the highest limit which is defined by the operator for all the chest, abdomen and pelvic regions. In most of the cases, the implemented tube current for chest, abdomen and pelvis were close (the total average STD of tube current=3.92 mA). The STD of tube current has a direct relationship with CV of all organs, but it was significant only for the total body, breast, and lungs (Pearson, P<0.05).

The average CV% of doses calculated by two methods were almost equal (P>0.05). However, the average CV% of total body effective dose for patients with BMI lower than 25 was greater for scans with 19 noise index. The parameter of effective area defined in this article, can be as a factor for assessment of efficiency modulating tube current. For patients with BMI higher than 25, the changes in tube current in Z-axis and the CV% of doses by two methods was greater for 22 noise index. The correlation between tube current and patient effective area was significant in 22 noise index (P<0.05). However, in patients with BMIs lower than 25, these changes were lower for the NI=22 group. In a very heavy patient with BMIs more than 35, the tube current patterns are almost the same for both noise indexes.

Table 3. CV% ±SD of doses calculated by regional and global CTDI, for two noise indexes of 19 and 22.

Organ	CV%±SD NI=19	CV%±SD NI=22
Total Body	12.05±3.57 (6.67 to 19.73)	12.68±4.23 (3.42 to 21.3)
breast	10.92±8.33(0.22 to 23.30)	12.3±7.59 (0.01 to 26)
gonads	9.93±6.05 (0.62 to 19.74)	8.95±5.92 (0 to 20.5)
Liver	7.62 ±6.51 (0.18to24.92)	8.58±6.85 (3.2 to 26)
Lung	10.27±5.93 (3.44 to 23.75)	12.35±5.36 (2.1 to 26.12)
RBM	6.46±8.05 (0.17 to 35.40)	5.39±6.59 (0.08 to 29.2)
thyroid	8.11±5.51 (0.89 to 20.16)	9.11±5.69 (0.62 to 24.2)
kidneys	6.69±8.86(1.49 to 26.88)	5.36±7.96 (3.59 to 28.21)
uterus	12.58±3.61 (7.58 to 17.22)	12.95±4.51 (6.59 to 16.36)

Table 4. Results of Independent T-test analysis for the effective dose calculated by Regional and Global CTDIvol for total body and separate organs.

Organ	Dose by Regional method(mSv) (mean±SD)	Dose by Global method (mSv)(mean±SD)	P-value
Total Body	10.79±2.147	9.64±1.96	*<0.001*
Breast	9.27±2.6	9.13±1.93	0.789
Gonads	11.72±3.34	11.22±3.03	0.093
Liver	11.17±2.36	10.79±2.03	*0.048*
Lung	12.55±2.78	11.81±2.31	*0.014*
RBM	2.71±0.58	2.59±0.5	*0.024*
Thyroid	19.06±4.16	18.37±4.19	0.127
Kidneys	12.28±2.63	11.67±2.21	*0.024*
Uterus	11.18±3.21	10.27±2.48	*0.038*

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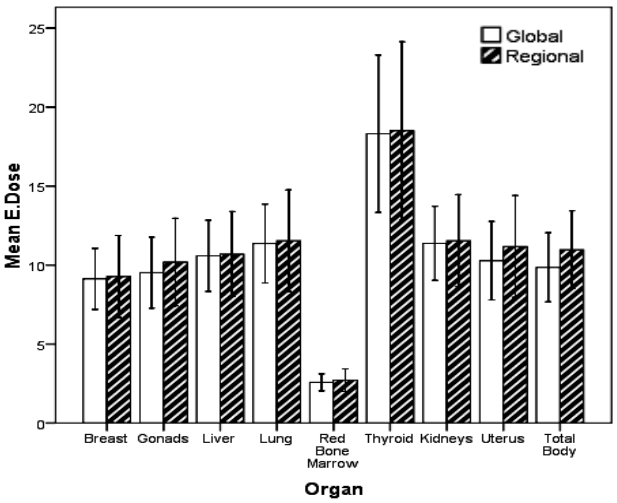


Figure 2. Effective Doses calculated by two methods for total body and specific organs for women (30 samples).

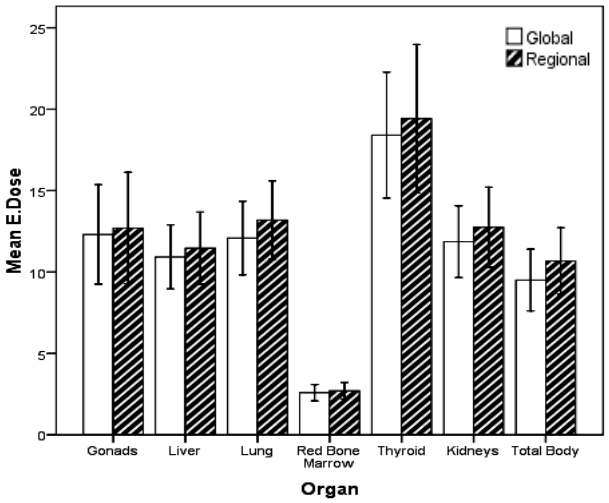


Figure 3. Effective Doses calculated by two methods for total body and specific organs for men (30 samples).

DISCUSSION

The noise index and mA range were defined to yield image quality accepted for the specific purpose of imaging. Reaching the highest limit of mA for all of the patients limited the ability of TCM method to act perfectly according to patient body's attenuation changes. Variations of tube current are strongly dependent on acquisition parameters, patient body's shape and diameter as demonstrated by Valeri *et al.* [10]. For the patient with smaller size, the CV of specific organs is greater because of successive modulation of mA in Z-axis. In this study, we compared the total body and specific sensitive organ doses by two methods of regional and global CTDI. It was demonstrated that the longitudinal TCM offers an acceptable approximation of detailed TCM methods as a reference [22]. The miscalculations in doses were not negligible for any of the organs. In terms of total body effective dose, the Global $CTDI_{vol}$ always underestimated a valuable parameter for risk estimation of the effective dose (3.42-21.3%); which is consistent with the study of Bostani et al, 2012. While for specific organs' dose calculations, the correlation is more complex. Although the $CTDI_{vol}$ is different from the patient dose [24], it is used as an alternative to estimate the effective dose in the clinic. The CTDI changes depend on patient situation, shape and attenuation. Our results revealed that the changes in dose calculation can be altered by noise index in different manners for patients with BMIs higher and lower than 25.

The most changes were for thyroid and breast (up to 30%) which is consistent with the study of Schlattl et al in pediatric [25]. Of course without mA limitation and free mA range, the variation in tube current and effective doses are larger to have an equal level of image noise [26]. However, for PET-CTAC semi-diagnostic approaches, this limitation is a clinical routine.

The use of fixed tube current is not an appropriate alternative [27]. Using conversion factors on regional DLPs to calculate the effective dose may be considered as an alternative approach for total body CT scans, but there is large approximations and it is not specific to patient circumstances or scanner model [28]. For total body CT, the AEC option of Impact Dose software guesses the tube current variations for normal patient body shapes and acquisition parameters [25]. By changing the noise index of Auto mA3D TCM method, the changes were different in patients with BMIs lower and higher than 25. This shows that the actually implemented pattern of tube current mainly depends on acquisition parameters and patients' body shape. Calculating the effective dose for total body PET-CT scans by using the Global $CTDI_{vol}$ leads to miss-estimation of total body and effective doses. The limited Z-axis regionally averaged mA must be considered. In

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order to calculate the total body and specific organs' effective dose, the Z-axis mA variation must be considered, which is related to variations of mA in Z-axis. The exact approach to calculate the effective dose in CT is a serious issue [9]. Using Monte-Carlo simulation and by considering the patient fitting to special phantoms and using exact data of CT tube and geometry is the most accurate method to calculate the effective doses [10, 29]; but it is time-consuming and common use in the clinic is almost impossible[9]. Impact as a user-friendly and simple solution to calculate the effective dose has some uncertainties in calculating the effective and organ doses in total body CT images.

CONCLUSION

To measure the patient dose in CT as part of total body PET-CT with Impact-Dose, just the Global CTDI is not the suitable method. The Regional CTDI must be considered. It is suggested to have an option for entering the mA table or curve of variation in Z-axis on Impact software and other pre-tabulated dose estimation software.

Limitations

Researchers are evaluated just one GE PET-CT system in present study and the data may not be Generalize to other scanners vendors. The higher level of tube current limits the changes in regional CTDI.

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Conflicts of interest*: *Declared none.

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